ACTIVE HUMAN INTELLIGENCE FOR SMART GRID (AHISG): FEEDBACK CONTROL OF REMOTE POWER SYSTEMS

A THESIS
SUBMITTED TO THE UNIVERSITY OF CANTERBURY
IN PARTIAL FULFILMENT OF THE REQUIREMENTS
FOR THE DEGREE OF
DOCTOR OF PHILOSOPHY

by
Miraz Mohamed Fulhu
April 2014

Department of Mechanical Engineering
College of Engineering
University of Canterbury
Christchurch, New Zealand

ACKNOWLEDGEMENTS

I am thankful to God for giving me patience, guidance and opportunities through all the people who helped me during this research. I would like to express my gratitude to everyone who supported me. The completion of this PhD thesis has been an exciting journey of both academic exploration and self-discovery which, would not have been possible without the continued support of some incredible people.

First of all, I would like to acknowledge the New Zealand Aid Programme (NZAID) for giving me the opportunity to study in this wonderful country through their scholarship. I would like to express utmost gratitude to my senior supervisor, Professor Susan Krumdieck, for her support, patience and encouragement throughout the research period. The basic foundation for this research comes from her remarkable, perceptive ideas and her gift of thinking beyond the boundaries. I was also fortunate to have Professor Pat Bodger as my assistant supervisor. His excellent and invaluable support was always available whenever it was needed. This research project progressed smoothly with the help of both of my wonderful supervisors and their invaluable comments, suggestions and directions.

Thanks to the entire Advanced Energy and Material Systems (AEMS) Laboratory crew. It was a pleasure working with such an exciting group. Thanks to Dr. Samuel Gyamfi for his support and valuable suggestions in the early stages when research questions were being developed. His ideas were a great initial step. A special thanks to Dr. Stacy Rendall for the help that was always available, whenever I needed it, throughout my research. Thanks to Dr. Abdulla Firag for the advice and help during the development of the MATLAB® simulation. A very special thanks to Dr. Muaviyath Mohamed for his continued support throughout my PhD research. He provided inspiration and support as a colleague, a close friend and as a brother.

A big thanks to the Maldivian community in Christchurch who helped my family and I feel at home during our stay here. Their warm and welcoming support during the most difficult times faced by everyone following the two major earthquakes (on 4 September 2010 and 22 February 2011) will always be treasured. We enjoyed every bit of the social gatherings, picnics and unforgettable trips.

Thank you to all of my family members and friends for their support and encouragement. This work would not have been possible if not for the hard work and determination of my parents in bringing me up or their nonstop encouragement for me to seek higher education. They have always been there for me and without them I would not be where I am today. Once again, a special thanks to "*bappa*" (Mohamed Ibrahim Fulhu) and "*mamma*" (Nasreena Ibrahim) for their constant support and strong belief in me. My deepest and most sincere thanks to my wonderful wife Fathimath Mohamed, for her endless love and encouragement. I cannot thank her enough for all the support and help she provided throughout the time we spent here, let alone since we met. I would not have reached this stage without her support, patience and trust in me. Furthermore, I could not have completed my work without my loving and wonderful children by my side. I am indebted to my daughter, Mariyam Mishka Miraz and my son, Mohamed Mish'aal Miraz for their unconditional love and patience during our long journey.

CONTENTS

List of Acronyms

A/S	*ancillary services market programs*
ADD	*average diversified demand*
AHISG	*active human intelligence smart grid*
BES	*battery energy storage*
BOP	*building occupancy profile*
CAP	*capacity market programs*
CO2	*carbon dioxide*
COE	*cost of energy*
CPP	*critical peak pricing*
CS1	*constraint scenario 1*
CS2	*constraint scenario 2*
CS3	*constraint scenario 3*
CS4	*constraint scenario 4*
DB	*demand bidding*
DG	*diesel generator*
DLC	*direct load control*
DR	*demand response*
DRP	*demand response programs*
DSM	*demand side management*
DUF	*demand use factor*
ED-CPP	*extreme day critical peak pricing*
EDP	*extreme day pricing*
EDRP	*emergency demand response programs*
EU	*european Union*
FFC	*forecasted fuel consumption*
GA	*genetic algorithm*
GDP	*gross domestic product*
GMD	*group maximum demand*
GUI	*graphic user interface*
HES	*hybrid energy system*
HOMER	*Hybrid Optimization Model for Electric Renewables*

HVF *hourly variation factor*

I/C *interruptible/curtailable programs*

IBP *incentive based programs*

IHDFI *in-house display / feedback interface*

LCOE *levelised cost of energy*

LPSP *loss of power supply probability*

LV *low voltage*

MCD *medium constrained demand*

MD *maximum demand*

MDD *maximum diversified demand*

ND *normal demand*

NREL *National Renewable Energy Laboratory*

OCS *operator control system*

PBP *price based programs*

PDR *participatory demand response*

PLC *power line communication*

PSO *particle swarm optimization*

PV *photovoltaic*

RAPS *remote area power supply*

RES *renewable energy sources*

RET *renewable energy technology*

RFC *real-time fuel consumption rate*

RTP *real-time pricing*

SCD *severely constrained demand*

SM *smart meter*

TBP *time based programs*

TOU *time of use*

UFCOCS *Uility-Fuel-Constraint Operator Control System*

VDR *voluntary demand response*

VPP *voluntary participation potential*

LIST OF FIGURES

LIST OF TABLES

ABSTRACT

Fuel supply issues are a major concern in remote island communities and this is an engineering field that needs to be analyzed in detail for transition to sustainable energy systems. Power generation in remote communities such as the islands of the Maldives relies on power generation systems primarily dependent on diesel generators. As a consequence, power generation is easily disrupted by factors such as the delay in transportation of diesel or rises in fuel price, which limits shipment quantity. People living in remote communities experience power outages often, but find them just as disruptive as people who are connected to national power grids. The use of renewable energy sources could help to improve this situation, however, such systems require huge initial investments. Remote power systems often operate with the help of financial support from profit-making private agencies and government funding. Therefore, investing in such hybrid systems is uncommon.

Current electrical power generation systems operating in remote communities adopt an open loop control system, where the power supplier generates power according to customer demand. In the event of generation constraints, the supplier has no choice but to limit the power supplied and this often results in power cuts. Most smart grids that are being established in developed grids adopt a closed loop feedback control system. The smart grids integrated with demand side management tools enable the power supplier to keep customers informed about their daily energy consumption. Electric utility companies use different demand response techniques to achieve peak energy demand reduction by eliciting behavior change. Their feedback information is commonly based on factors such as cost of energy, environmental concerns (carbon

dioxide intensity) and the risk of black-outs due to peak loads. However, there is no information available on the significant link between the constraints in resources and the feedback to the customers. In resource-constrained power grids such as those in remote areas, there is a critical relationship between customer demand and the availability of power generation resources.

This thesis develops a feedback control strategy that can be adopted by the electrical power suppliers to manage a resource-constrained remote electric power grid such that the most essential load requirements of the customers are always met. The control design introduces a new concept of demand response called participatory demand response (PDR). PDR technique involves cooperative behavior of the entire community to achieve quality of life objectives. It proposes the idea that if customers understand the level of constraint faced by the supplier, they will voluntarily participate in managing their loads, rather than just responding to a rise in the cost of energy. Implementation of the PDR design in a mini-grid consists of four main steps. First, the end-use loads have to be characterized using energy audits, and then they have to be classified further into three different levels of essentiality. Second, the utility records have to be obtained and the hourly variation factors for the appliances have to be calculated. Third, the reference demand curves have to be generated. Finally, the operator control system has to be designed and applied to train the utility operators.

A PDR case study was conducted in the Maldives, on the island of Fenfushi. The results show that a significant reduction in energy use was achieved by implementing the PDR design on the island. The overall results from five different constraint scenarios practiced on the island showed that during medium constrained situations, load reductions varied between 4.5kW (5.8%) and 7.7kW (11.3%). A reduction of as much as 10.7kW (15%) was achieved from the community during a severely constrained situation.

Chapter 1

Introduction

The aim of this chapter is to provide introductory material on the research work presented in this thesis. The motivation and objectives behind the research presented are detailed in sections 1.1 and 1.2, respectively. In sections 1.3 and 1.4, research outcomes and thesis organization are discussed.

1.1 Motivation

The electrical power grid is undoubtedly the most important technical infrastructure available today and can be considered the foundation for modern life. It is considered the basic building block of modern industrial economies, and future economic growth is critically dependent on it (Ayres, 2008). Furthermore, most of the essential services associated with human well-being depend on the quality of electric power available. For this reason, a reliable and secure supply of electricity is of utmost importance for society.

After the commercial generation of electricity in the nineteenth century, there was a tremendous increase in world development and population. Population has tripled since the late 1930s, resulting in more demand for energy (Jeffs, 2010; Tester, Drake, Driscoll, Golay, & Peters, 2005). At present, the main source of energy is from fossil fuels—namely coal, oil and gas—providing more than 85% of primary energy demand. However, the increase in this form of energy use has led to a huge increase in the amount of carbon dioxide discharged into the atmosphere. Burning fossil fuels for electricity generation alone accounts for 22% of global greenhouse gas emissions (Jeffs, 2010). Thus, creating a reliable and efficient power system that is both sustainable and environmentally friendly has become more of a challenge.

One of the preferred solutions to this problem is the use of renewable energy technology (RET), namely solar photovoltaic (PV) and wind-power, coupled with battery energy storage (BES). These technologies have been integrated into diesel generator (DG) systems to reduce the consumption of fuel. While integrating these technologies into DG systems reduces the cost of generating energy, the overall capital costs of these systems is relatively prohibitive when compared to DG only systems, at least this was the case until oil prices increased. Increasing oil prices during last few years have made the reduction of fuel consumption a goal in power generation not only for economic reasons, but also for reliability concerns. In most of the diesel generator - renewable energy technology (DG-RET) hybrid systems, diesel generators are used as a support system that only kick in when the RET system is unable to supply the requested power (Ashok, 2007).

Peak demand is another considerable problem for both the security and cost of generation in power systems. Peak demand is the maximum demand any particular system reaches within a considered duration. As it is, this is not a problem. The problem with peak demand arises when the difference between the peak demand and the next closest demand value is considerably greater. Some load control strategies for peak demand management and load shape management have been implemented and are now being used by energy providers. Demand response (DR) is a demand side management (DSM) tool that is being used to manage peak demand by influencing human behavior. There are various types of information that can be fed back to consumers to bring about a necessary change in behavioral patterns. Studies have shown that security, environmental concern and price are factors that receive consumer attention (Gyamfi, Krumdieck, & Brachkney, 2009).

Serious energy supply issues and environmental problems, however, cannot be addressed by economics, engineering and science independently (Krumdieck, 2007). Krumdieck (2007) proposes that projects such as the integration of RET into power systems or considering consumer behavior changes using demand side management tools are simply focusing on a component-level, while a system-level, multidisciplinary approach is required to achieve a sustainable solution. As a consequence, new control mechanisms need to be developed to incorporate the regional energy system constraints into the relationship between electrical power suppliers and their consumers. To design such control mechanisms, an understanding of how the basic feedback control system functions is mandatory. The standard presentation of a feedback control system design is illustrated in Figure 1.1.

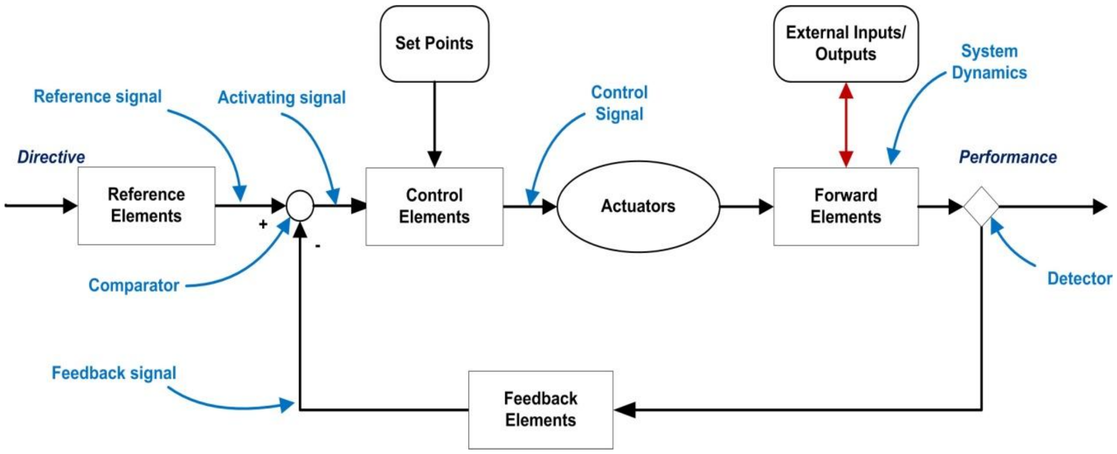


Figure 1.1: Standard presentation of a feedback control system (Krumdieck 2007)

In Figure 1.1, the directive, or the system goal, is represented by the input reference elements. The comparator determines the difference between the reference signal and the feedback signal. This difference is fed to the control elements as the activating signal. The control elements convert the activating signal to a control signal, based on pre-existing set points, which in turn causes physical changes in the system actuators. The actuators affect the performance of the forward elements, which represent the physical plant. The system performance or the actual system behavior is measured by detectors and feedback elements convert this detector signals to the same calibration as the reference signal.

If the operation of a power generation system is used as an example of a feedback control system, the directive would be the desired load by the customers. In this case, the performance would be the actual load generated. The set points would be the system voltage and frequency. The actuator would be the generator's fuel supply controller, or the governor, and the external input would be the diesel fuel. All these affect the forward elements which, in this case, would be the diesel generators. Transducers detect the actual load generated, and the electronic calibrators, or feedback elements, feed the signal back to the comparator. The importance of signal processors in sustainable operation of a system is illustrated in this example. However, the controller will only operate according to its pre-existing design and cannot bring about any changes on its own.

This example shows that in the power generation system, there is no feedback link between the availability of diesel fuel and the system directives. Hence, in case of a fuel availability constraint, the controller does not have any feedback signal that can activate the customers to reduce their demand. This thesis develops a feedback control system that addresses the aforementioned link required for sustainable power generation in a remote electric power grid.

1.2 Objectives

The main purpose of the research presented in this thesis is to develop and evaluate a real-time feedback control strategy of a resource-constrained remote electric power grid using *participatory demand response (PDR)*. Different methods of demand control for power grids are already being used by different electrical providers. The method adopted in this research has not yet been attempted and this is supported by the literature review in Chapter 2. The PhD research presented herein sought to meet the following objectives:

- Investigate the resource constraints in remote electric power grids.

- Review the types of feedback control strategies being used in mitigating resource constraints in remote power grids.

- Design a control strategy that integrates consumer participation in managing the community electric power demand.
- Implement this design into a remote power grid to validate the key concepts.

1.3 Outcomes

The main contribution of this research is a real-time feedback control strategy for a resource-constrained remote power grid using a novel concept introduced as participatory demand response (PDR). In addition to this main contribution, the following outcomes are achieved:

- Classification of end-use load into three levels of essentiality, namely deferrable, optional and essential loads.
- An energy audit and energy survey methodology for a remote island community.
- Three levels of voluntary participation potential from the consumers. These levels are used as reference load curves and are generated using the concept of maximum diversified demand.
- A computer-based utility operator control system named *Utility-Fuel-Constraint Operator Control System* (UFCOCS).
- The introduction of an electrical demand forecast methodology that utilizes a *demand-use-factor* (DUF) matrix.
- An estimated hourly variation factors (HVF) table for the island of Fenfushi, which can be used in similar remote islands in the Maldives.

1.4 Thesis Organization

While organizing the chapters of this thesis, every attempt was made to provide a logical sequence of information, from reviewing the available literature to the application and testing of the developed methodology. A brief description of the chapters that follow is provided below.

- **Chapter 2:** This chapter provides a critical review of the literature on the remote area power supply systems and different control strategies being used to manage energy demand.

- **Chapter 3:** The theory of participatory demand response (PDR) is covered in this chapter, which provides an explanation of the main concepts as well as the control system design concepts.

- **Chapter 4:** This chapter provides a detailed description of the implementation procedure for introducing the developed PDR control system into a remote electric power grid.

- **Chapter 5:** The concept validation procedure, including case study scenarios, for the PDR system developed in this thesis is discussed in this chapter.

- **Chapter 6:** This chapter presents the evaluation results of the PDR system developed in this research. The statistical analysis carried out for the scenarios developed in Chapter 5 for validating the PDR model are presented, along with the energy audit and survey results.

- **Chapter 7:** Conclusions, recommendations and suggestions for future work are discussed in this chapter.

CHAPTER 2

LITERATURE REVIEW

"You can never have an impact on society if you have not changed yourself"

-Nelson Mandela-

ENERGY is a commodity that is essential to everyone in modern society. It is a requirement for all of our everyday services. However, energy supply and consumption is also an issue that many do not think about until they are confronted with an energy crisis. Remote communities face different kinds of energy crisis on a frequent basis, which will be explained in this chapter.

The aim of this chapter is to provide a critical review on remote area power supply systems and different control strategies being used to manage energy demand. Section 2.1 is an introduction to remote area power supply (RAPS) systems. Section 2.2 reviews the control strategies utilized in RAPS systems. A review of the developing smart grid technology is presented in section 2.3. Section 2.4 explains how the end-use load can be characterized in order to manage the energy being consumed by a community. Section 2.5 reviews human behaviour in the context of energy use. Section 2.6 reviews demand side management and demand response techniques. Section 2.7 presents literature on energy audits and surveys. Section 2.8 reviews the techniques used in energy modelling, including the method of diversified demand employed throughout this thesis. The chapter is summarized in section 2.9.

2.1 Remote area power supply (RAPS) systems

Maintaining a secure and reliable power supply in remote areas is a major challenge for energy engineers and the utility industry. Installation of distribution lines from an existing national grid is considered uneconomical due to factors such as difficult geographical terrain for a line to go through and the low level of load that needs to be supplied (Mondal, Kamp, & Pachova, 2010). Remote power by grid extension also suffers from low power quality and high transmission and distribution losses (Ambia, Islam, Shoeb, Maruf, & Mohsin, 2010; Moharil & Kulkarni, 2009). The most viable solution for supplying power to remote communities is by installing a local mini-grid that satisfies the community demand.

2.1.1 Mini-grids

A mini-grid can be defined as a low voltage (LV) electricity distribution network that supplies a localized electricity demand and consist of power generation from various energy sources, electrical energy storage devices and control mechanisms (Berry, Platt, & Cornforth, 2010; ESMAP, 2000). A lot of remote power supplies depend on diesel generators (DGs) as their primary source of energy. However, over the recent decade, the high costs, fuel transportation, storage and acquisition of diesel are becoming more problematic (Breyer, Gerlach, Schafer, & Schmid, 2010). Renewable energy sources (RES) combined with diesel fuel systems are used to minimize fuel consumption and consequently, dependence on diesel fuel. Figure 2.1 shows the general schematic of a remote mini-grid.

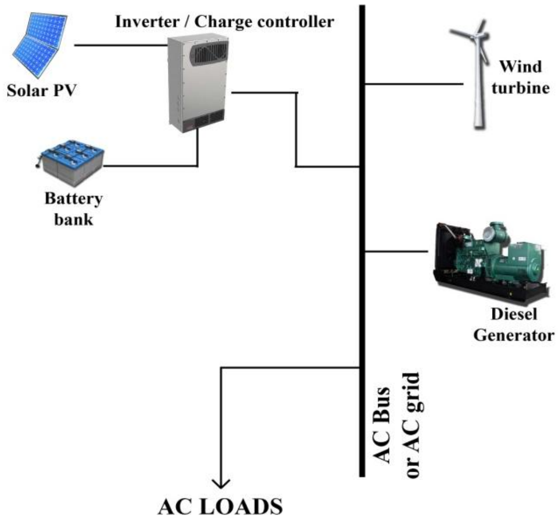


Figure 2.1: General schematic of a remote mini-grid

Most remote power supplies have at least two diesel generators, often with different capacities, in a powerhouse serviced by local operators (van Alphen, van Sark, & Hekkert, 2007). The normal operating regime for a remote power generation system servicing a mini-grid involves running one generator at a time with manual roll-over between generators of different sizes to accommodate the normally expected peak loads or anticipated load drop-offs. Synchronous operation of multiple generators with automatic roll-over is much more expensive than manual operation. Remote areas typically have load patterns with peaks at morning and evening meal times, and minimums during mid-day and night (Camerlynck, 2004; Ijumba & Singh, 2004; Underwood, Ramachandran, Giddings, & Alwan, 2007). These patterns are used by the local operator to decide on the appropriate generator to use and the time for roll-over. This type of operating scheme is basically open-flow control with prescribed set point management and little or no real-time analysis or management.

2.1.2 Energy sources

The main source of energy for RAPS systems is still the diesel generator. Low initial investment, the low cost of energy (COE) and the simplicity of its deployment makes it the initial choice for power generation in remote areas (Zhang, Tan, Li, Li, & Feng, 2013). However, with the rise in oil price and other maintenance concerns, RES are making their way into the RAPS systems. Also, the decrease in the price of photovoltaic (PV) modules over the last five years has resulted in the levelized cost of energy (LCOE) of PV being lower than that of the diesel generators (Branker, Pathak,

& Pearce, 2011). LCOE is the complete life cycle cost of a power generating technology per unit of electricity, and is expressed in $/kWh. LCOE allows comparison of different modes of generation despite the difference in their cost structures (Ueckerdt, Hirth, Luderer, & Edenhofer, 2013).

The main drawback of using RES such as solar and wind is the fluctuating nature of their availability. Solar PV systems require sunlight, hence they are limited to the time when radiation from the sun is available. Similarly, wind turbines only generate electric power when there is enough wind for the generator to operate. Unlike fossil fuels, sunshine and wind can be neither stored nor transported to their place of use. They need to be converted to another form such as electricity, which is then either transmitted or stored.

One of the most common forms of electricity storage in power systems is the lead-acid battery. The main problem with this form of storage is that it can store only a comparatively small amount of electrical energy compared to the amount normally required for consumption. The other disadvantage of using battery energy storage (BES) is the losses involved. *Coulombic losses* and *Voltaic losses* (Dell & Rand, 2001) are examples of losses that may occur in the batteries. Coulombic loss, or coulombic inefficiency, can be defined as the electrical current wasted in non-productive side reactions; corrosion in battery components is an example. Voltaic loss, or voltaic inefficiency, is the measure of the difference between the charging and discharging voltage. The voltage required to charge a battery is always greater than the discharge voltage. Due to these losses, the overall electrical efficiency for electrochemical processes generally falls in the range of $50-75\%$. As a result, a system including BES becomes costly in terms of installation as well as operation and maintenance (Su, Huang, & Lin, 2001).

2.1.3 Hybrid systems

A hybrid energy system (HES) is comprised of two or more sources of energy that are being utilized in either stand-alone or grid-connected mode (Kusakana & Vermaak, In press). It can work utilizing two or more renewable energy sources or it can be composed of both renewable and conventional sources of energy. The critical feature of a HES is that it can combine two or more renewable sources in order to get the best system dynamics depending on their operating characteristics. Thus, the use of a hybrid system can improve overall flexibility, reliability and efficiency of the electric power system (Shaahid & Elhadidy, 2007; Urbanetz, Braun, & Rüther, 2012).

Hybrid systems are becoming a more accepted option for remote power generation systems. There are two main reasons for power generation using hybrid systems in remote areas. Independent use of RES results in over-sizing the system due to reliability concerns, which increases the investment cost. Similarly, independent use of a diesel-only system can have high operation and maintenance costs, even though the initial investment is low (Elhadidy & Shaahid, 2000). A hybrid system consisting of RES coupled with DGs can be considered one of the best options for RAPS systems. Such hybrid systems can achieve a high rate of renewable energy penetration and also maintain a stable supply of electric power (Rehman & Al-Hadhrami, 2010; Segurado, Krajačić, Duić, & Alves, 2011). In an Alaskan village, by upgrading the DG stand-alone system to a DG-Wind hybrid power system, the power suppliers were able to get a 50% reduction in diesel fuel consumption. Furthermore, they also achieved a 30% saving in the annualized cost (Clark & Isherwood, 2004).

To utilize the hybrid system efficiently and economically, it should be sized accordingly, such that it operates in the most optimum conditions in terms of investment and system reliability. Different optimization techniques are being used and have been reported in the literature. (Zhang, et al., 2013) presented a method for the component sizing of hybrid systems based on the optimization of power dispatch simulations. This methodology involved evaluating and minimizing the COE in the system power dispatch simulations, which included the capital depreciation cost, fuel cost, emissions damage cost, and also the maintenance and replacement cost of the entire project life cycle.

Genetic algorithm (GA) is an optimization technique that is used to obtain solutions to complex problems. This technique is based on the genetic process of biological organisms proposed by Charles Darwin (Chen & Huang, 2008). An optimum sizing method for a hybrid PV-Wind system was developed by (Yang, Wei, & Chengzhi, 2009) based on the concept of a GA. The model they presented can calculate the optimum system configurations in order to achieve the desired loss of power supply probability (LPSP), while ensuring that the annualized cost of the system stays at a minimum. (Kalantar & Mousavi G, 2010) also presented a hybrid system optimization methodology based on economic analysis using GA. The hybrid system, which can be used to supply electricity to isolated rural areas, consisted of a wind turbine, a solar array, a micro-turbine and a battery bank.

Particle swarm optimization (PSO) is another technique that is used for hybrid system sizing optimization. It is based on the theory of swarming, and belongs to the evolutionary computation techniques (Kennedy & Eberhart, 1995). The PSO technique was used by (Sa, x, nchez, Ramirez, & Arriaga, 2010) for the optimal sizing of a hybrid system such that the demand of an isolated load is met. The methodology developed allowed calculation of the best system configuration that could deliver the required energy supply reliably, while maintaining a desirable level of system economics. (Mohammadi, Hosseinian, & Gharehpetian, 2012) also presented a method that utilizes the PSO technique for optimizing the design of a micro-grid with a hybrid system consisting of a PV array, wind turbine and a battery bank for energy storage. The optimization algorithm developed was applied to an LV network which was operating under different market policies, in order to obtain the minimum micro-grid cost.

Literature has also shown the use of other optimization techniques such as simulated annealing (Ekren & Ekren, 2010), neural networks (Mellit & Benghanem, 2007; Mellit, Kalogirou, & Drif, 2010) and stochastic approaches (Kaplani & Kaplanis, 2012; Z. Zhou et al., 2013). Apart from the few described above, more techniques are available in the literature dedicated to hybrid system optimum sizing.

Hybrid system optimization can also be carried out by using simulation programs purpose built for evaluating the performance of such systems. The most commonly utilized program for this is the Hybrid Optimization Model for Electric Renewables (HOMER), developed by the National Renewable Energy Laboratory (NREL). HOMER is a software that computes and evaluates multiple design options for both grid-connected and off-grid power systems. The program can model both conventional technology and RETs, and perform the economic and technical feasibility of a wide range of technology options to account for variations in costs and energy resource availability (Sureshkumar, Manoharan, & Ramalakshmi, 2012). Further literature on both HOMER and various other simulation programs can be found in (Belmili, Haddadi, Bacha, Almi, & Bendib, 2014).

2.2 Control strategies utilized in RAPS systems

Most remote power systems often suffer from security issues such as brown-outs and black-outs, and power reliability issues such as frequency and voltage fluctuations. Security of power can be threatened by natural phenomena such as meteorological issues, or accidental problems such as equipment malfunctions and operational failures (Bompard, Huang, Wu, & Cremenescu, 2013). In stand-alone diesel generator systems, failure in fuel delivery or shut-down of a generator can lead to serious security issues. Similarly, low wind and solar radiation can disrupt the power supply from wind turbines and solar PV systems. To minimize these threats, as discussed in **section 2.1.3**, hybrid systems are becoming a popular technology for the power generation sector in remote power systems. However, the use of RES augments concerns for power reliability issues, such as frequency and voltage fluctuations, due to the intermittent nature of their availability. To reduce these fluctuations, the use of energy storage devices such as batteries has been adopted by power engineers (Ali Nandar, 2013).

Three types of strategies are practiced as control strategies in RAPS systems. The initial strategy utilized in remote power systems is to have a power availability time schedule. This is to ensure that the system is able to operate at times when the customers require it most, and the supply schedule remains uninterrupted throughout the month. These types of scheduled systems normally incorporate a single diesel generator. An example for a time scheduled operation is the power supply on the coral atolls of Tokelau. In Tokelau electricity is supplied from around 7.00 or 8.00 a.m. until 3.00 or 4.00 p.m. during day time. The evening supply is from around 5.30 p.m. until around midnight (Hamm, 2007).

A second strategy is to incorporate a *rolling blackout* or *rotational load shedding*. This type of load shedding is an electrical power shutdown that is intentionally engineered to avoid a complete blackout when there are constraints in the systems (Billinton & Satish, 1996). A rolling blackout is generally triggered due to constraints in power generation or as a result of failures in distribution infrastructure. For example, as a result of the attempted coup in the Maldives on 3 November 1988 (Singh, 2012), all the islands in the Maldives were advised to generate power only at specific times of the day in order to minimize the use of diesel fuel. This measure was taken by the government in response to the shortage in fuel and its availability during the time of national emergency.

The most recent strategy is the use of hybrid systems for RAPS. Remote hybrid power systems with RES normally incorporate a diesel generator or a battery bank (sometimes both) as a backup source for periods when the renewable resource is insufficient in meeting the demand. Hybrid systems reduce the amount of risk on the system security due to the reduction in conventional fuel use. As a backup source, a diesel generator improves system reliability by supplying the system with the power required when renewable sources are unable to meet the demand (Merei, Berger, & Sauer, 2013). Batteries are normally used to enhance system reliability by minimizing the sudden surges in frequency and voltage caused by fluctuations in the RES (Aghamohammadi & Abdolahinia, 2014; Tan, Li, & Wang, 2013). When the system is generating more power than required, the excess power is used to charge the battery bank, which can later be discharged into the grid to fill in any unmet load.

2.3 Smart grid

The traditional power grid is considered a centralized and service provider controlled network system. It acts as a network with a one-way transmission of power that flows from the generating station to the consumers. In most developed countries there is no consumption limit for end-users and the supplier is responsible for supplying the consumers' fluctuating demands (Crossley & Beviz, 2010). This fluctuation can be problematic when demand starts to outgrow what the supplier can provide. Under such circumstances, without a feedback technology, the electric power grid can be a difficult system to operate. As a result, it is of utmost importance to change the power grid into a much smarter one.

There is no set definition for a smart grid. In more general terms, a smart grid can be defined as a modern electric power grid that is technically superior and sustainable compared to the traditional grid. Such a system should have well established communication and monitoring capabilities (Wang, Xu, & Khanna, 2011), and enhanced control and management functionalities (Mei & Zhu, 2013). The feedback technology incorporated into a smart grid should keep both the utility company and the consumer updated.

While smart grids are already being developed by some countries, a few countries such as the United States have already started to implement the technology (Ghosh, Pipattanasomporn, & Rahman, 2013). Countries including Korea (Sung-Yong & Beom-Jin, 2009), India (Mukhopadhyay, Soonee, Joshi, & Rajput, 2012) and China (Uslar, Rohjans, & Specht, 2012) are concentrating on implementing such systems in the near future. Even though China has not fully implemented the use of smart grids, they have been leading the smart grid technology implementing process amongst the developing economies (Nejad, Saberian, Hizam, Radzi, & Ab Kadir, 2013). Of the top ten countries for federal investments on smart grids in the year 2010, China led with an investment of US$7.32 billion (Ghosh, et al., 2013).

The simplest form of the smart grid has four features:

- an in-house display and smart feedback interface
- a smart meter for monitoring energy usage
- a technically enhanced bidirectional communication−enabled distribution network
- a supplier side interface

The aim of installing an in-house display/feedback-interface (IHDFI) is to encourage energy−conscious behaviour amongst the residents of a particular household. An IHDFI installed where it is easily accessible to the consumer can provide knowledge about daily energy consumption and motivation in regards to energy management. Depending on the amount of detail or motivation required by the user, displays can be installed centrally (one per household) or they can be installed in different areas of the dwelling (Wood & Newborough, 2007). The information displayed should be categorized and conveyed effectively in order to promote energy-saving behaviour. Studies have shown that proper layout and quality of feedback could result in achieving energy savings of 5%−15% (Burgess & Nye, 2008; Darby, 2006). Detailed research on the key design specifications of this type of display has been carried out by (Anderson & White, 2009).

The level of information required by the IHDFI cannot be monitored by traditional meters with rotating disks. To display appropriate and precise energy consumption details, advanced digital meters that can monitor real-time energy consumption data are required. Such digital meters, also called *smart meters* (SM), must be able to record hourly or more frequent end-use consumption, and transmit the data over a communication network to the utility provider (Ehrhardt-Martinez, Donnelly, & Laitner, 2010). This makes the SM one of the most critical devices required by the smart grid. Using the SM offers several advantages:

- enabling two-way communication between consumers and suppliers
- enabling suppliers to better manage the demand during peak load times
- enabling more accurate billing for consumers
- enabling implementation of better tariff models

In the European Union (EU), Italy's penetration rate for smart meters has reached 85%, while France, Ireland, the Netherlands, Norway and Spain project to completely switch over to SM technology by the year 2020 (Faruqui, Harris, & Hledik, 2010). In the United States, there were a total of 36 million smart meters installed as of May 2012. This number is estimated to reach approximately 65 million units by the year 2015 (I.E.E., 2012).

The next most important component of the smart grid is the bidirectional communication−enabled distribution network. The effective use of SMs and IHDFIs is not possible without a well developed distribution network. The distribution network of a smart grid is responsible for both transmission of electricity and also the much sophisticated communication capabilities. The enhanced functions, made possible by the communication network, increase the reliability of the entire distribution network (Celli, Ghiani, Pilo, & Soma, 2013). These enhanced functions can introduce self-healing of the network to reduce interruption time, and carry out intentional islanding to improve reliability (Brown, Suryanarayanan, & Heydt, 2010), since feeder-level component failures account for almost 80% of consumer interruptions (Hammoudeh, Mancilla-David, Selman, & Papantoni-Kazakos, 2013). Different methods of incorporating communications technology into the smart grid have been tested. Some of these include internet based architecture, power line communication (PLC) architecture and wireless networks (Gao, Xiao, Liu, Liang, & Chen, 2012).

The fourth main component of the smart grid is the supplier side control interface. One of the fundamental operations of the supplier is to ensure that consumer demand is met. The supplier must be able to monitor the entire network in order to maintain a reliable and secure power grid. With the help of a smart monitoring system, the supplier is able to conduct different demand side management activities like real-time pricing or direct load control, which can help in maintaining a healthy power grid. The smarter control interface also enables the supplier to integrate different types of power generation technologies, such as solar PV and wind energy, hence reducing the utilization of fossil fuels for power generation (Alagoz, Kaygusuz, & Karabiber, 2012; Järventausta, Repo, Rautiainen, & Partanen, 2010).

2.4 End-use load characterization

The end-use electrical demand of any community can be broadly classified into three main categories. These include governmental demand, commercial or industrial demand and residential demand.

- Governmental demand

  The governmental demand sector of most remote island communities consists of places such as community offices, health centres and, in some places, telecommunications offices. In more developed island communities a small bank can also be present.

- Commercial / Industrial demand

  In most remote areas this sector mostly consists of small businesses such as retail shops and cafés. In some island communities it can also include commercial facilities such as boat yards where boats are built and repaired.

- Residential demand

  This is the electrical load required by the residential sector of the community. While residential energy is responsible for about a third of total global energy use (IEA, 2008), it is the main sector contributing to the maximum demand within a remote community. Residential end-use equipment can vary from electrical lighting to high power consuming devices such as air-conditioners. Of all household end-use appliances, refrigerators, TVs, washing machines, electric irons and air-conditioners account for the highest consumption of electricity (Daioglou, van Ruijven, & van Vuuren, 2012; Rosas-Flores & Gálvez, 2010). However, the majority of consumers have no knowledge of which appliance in their household consume the most energy. In a study conducted by (Mansouri, Newborough, & Probert, 1996), when residents were asked about the first, second and third most energy consuming electrical appliances in their household, the majority of respondents selected the washing machine, while the top three energy consumers were the lighting, freezer and dishwasher.

Each of the three categories of demand mentioned above can be further classified into *deferrable*, *optional* and *essential* loads, depending on the essentiality of each of the appliances. A deferrable load can be defined as the power consumed by an appliance that can have its time of utilization deferred within the day or the week. Deferrable load can also include those appliances that can be totally isolated from the grid until a constraint has subsided. For example, in remote island communities, the use of a washing machine can be replaced by washing by hand.

Optional loads are defined as the power consumed by an appliance or group of appliances that can have their consumption reduced at any given time of the day. The reduced consumption, as with reducing the number of lights being used at a particular time, should not have a negative effect on the health and wellbeing of consumers.

These loads are different from deferrable loads in the sense that these loads cannot be completely taken off grid. Optional loads can vary from person to person or from household to household.

The essential loads are defined as the power consumed by appliances that, if power demands were unmet and these appliances failed, would have a negative impact on the health and wellbeing of consumers. During an energy audit and survey, these loads should be very clearly identified. The aim of the power supplier should always be to provide this load to the consumer. In a lot of places, an example of such a load would be the fridge/freezer.

By classifying the end-use load into these categories, it is easier for an energy engineer to design a demand response program. To acquire this information it is important to carry out an energy audit survey. However, before designing a survey, consumer behavior towards energy use should be understood.

2.5 Human behavior in the context of energy use

Researchers on human behavioral psychology have been exploring the internal motivations of individual energy consumption behavior. According to research undertaken by (Katzev & Johnson, 1983), providing consumers with detailed feedback on their energy consumption is much more effective in conserving energy than providing them with monetary incentives for load curtailment or information on the energy crisis and the specific steps to be taken to conserve energy. The authors also pointed out that the percentage involvement of the consumers in energy related tasks triggers energy conserving behaviors. (Heberlein & Warriner, 1983) also found that energy conserving behavior could be triggered by detailed feedback alone, without any monetary incentives. Their models showed that the main factor influencing conservation was the individual's personal sense of commitment. This is highly independent of monetary incentives. Other drivers for the conservation of energy include the consumer's personal “intrinsic satisfaction” (De Young, 1996), guilt (Bamberg, Hunecke, & Blöbaum, 2007) and moral responsibility for the use of energy (Kaiser & Shimoda, 1999).

The theory of planned behavior (Ajzen, 1991) is another model that is often used in psychological studies. This is an extended version of the theory of reasoned actions. This theory states behavior is explained by an individual's *intention* (*BI*) to engage in a particular behavior. The individual's *intention* depends on his or her *attitude* (A) towards that behavior, or how the individual evaluates the given behavior, and the *subjective norm* (*SN*), which is a social factor and depends on the social pressure to carry out a particular behavior (Ajzen & Madden, 1986). Perceived behavioral control is the third factor that determines behavioral intentions (Ajzen, 1991). Perceived behavioral control (*PBC*) is a measure of an individual's perception towards carrying out a given behavior, which may vary depending on the situation and type of action (Ho, Tsai, & Day, 2011). Figure 2.2 shows a structural diagram of the theory of planned behavior.

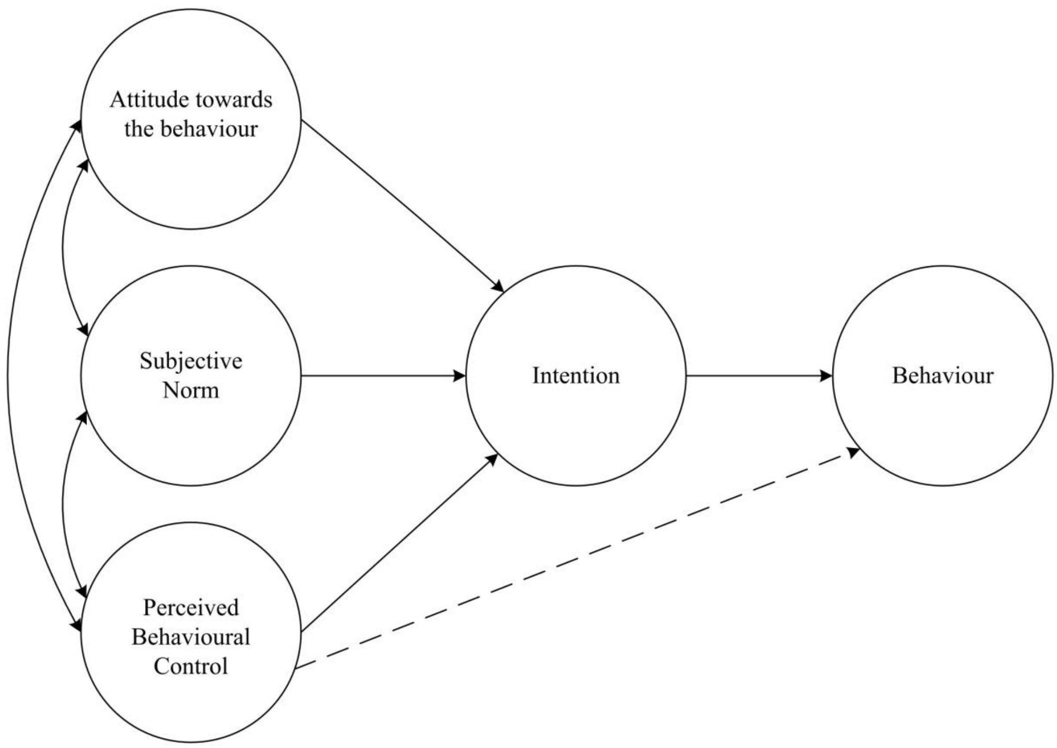


Figure 2.2: Structural diagram of the Theory of Planned Behavior (Ajzen 1991)

The theory is mathematically represented by the equation:

$$BI = w_1 A + w_2 SN + w_3 PBC = w_1 \sum b_i e_i + w_2 \sum nb_j mc_j + w_3 \sum cb_k pf_k \qquad \textbf{Eq. 1}$$

where w_1, w_2 and w_3 are regression weight correction factors. The attitude is further specified as individual salient beliefs (b_i) about a relevant attribute, multiplied by the evaluations (e_i) of those attributes. Subjective norms are given as the product of the normative beliefs (nb_j) multiplied by the motivation to comply (mc_j) to those. The perceived behavioral control is comprised of the sum of the control beliefs (cb_k) multiplied by the perceived facilitation (pf_k) of the control factors (Ho, et al., 2011).

The theory of planned behavior is considered to be a good predictor of behavior and has been used to predict hygienic food handling behaviors (Mullan & Wong, 2009; Phillip & Anita, 2010), predict bad driving habits (Chan, Wu, & Hung, 2010; Forward, 2009; Moan & Rise) and predict eco-friendly activities (Han, Hsu, & Sheu, 2010; Tonglet, Phillips, & Read, 2004)

2.6 Demand side management and demand response

In the late 1970s when demand side management (DSM) programs were first introduced, they were aimed at creating awareness of energy conservation amongst customers. Load management programs came into practice in the 1980's and by the end of the decade, DSM activities were widespread (Bock, 1998; Gellings & Chamberlin, 1993). The most widely accepted definition of DSM is:

> *"Demand Side Management is the planning, implementation, and monitoring of those utility activities designed to influence customer use of electricity in ways that will produce desired changes in the utility's load shape, i.e., changes in the time pattern and magnitude of a utility's load" (Gellings, 1985).*

The definition leads to six load shape objectives, or activities, that can be taken into consideration during DSM planning, namely peak clipping, load shifting, strategic conservation, strategic load growth, valley filling and flexible load shape (Gellings & Smith, 1989; Grover & Pretorius, 2007), as shown in Figure 2.3.

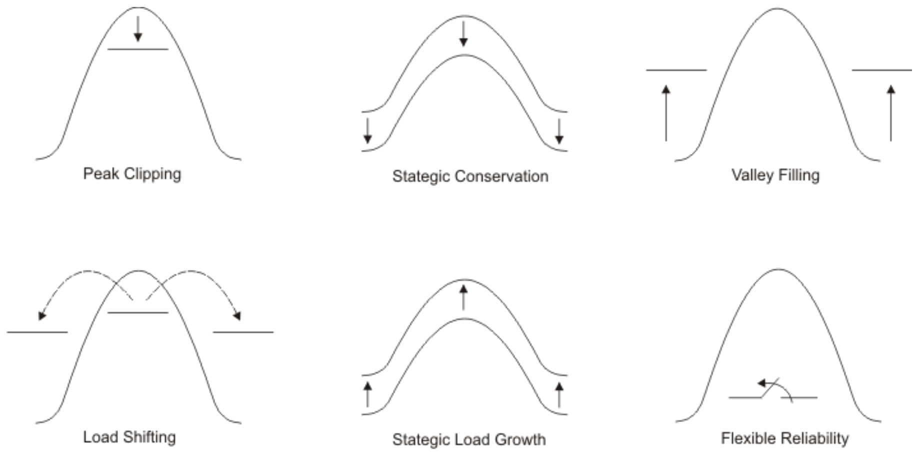


Figure 2.3: Demand side management activities

(source:(Gellings and Smith 1989; Grover and Pretorius 2007))

DSM techniques are now being practiced by power suppliers in most countries to manage peak demand issues (Qureshi, Nair, & Farid, 2011; Rankin & Rousseau, 2008). Utility providers use different activities either directly caused or indirectly stimulated by the provider, that are designed to influence customers to consume electricity in such a way that the utility load curve is in a desired form (Grover & Pretorius, 2008).

Demand response (DR) is a DSM technique that involves participation of end-users where they respond to signals given by the electrical power suppliers by managing the amount of energy used (Kwag & Kim, 2012). Studies have shown that when end-users are aware of their usage, they tend to manage their total consumption to some extent. Large differences have been observed in end-users' preferred feedback mechanisms, depending on factors such as dwelling type, age of the 'head of household' and energy consumption levels (Vassileva, Odlare, Wallin, & Dahlquist, 2012).

A study carried out by Ueno et al. reported that household energy consumption was reduced by 18% due to a rise in energy-consciousness of the household members, who used an interactive web page to view energy consumption data. Ueno et al. (2006) developed two web based systems, ECOIS and ECOIS II. These systems displayed information on the room temperature, gas consumption of the whole house, power consumption of up to 18 different appliances and total power consumed. When consumers were provided with data on the power consumption of different appliances, there was a 12% reduction in power consumed by the appliances displayed. A 5% reduction in power consumption by appliances that were not displayed was also observed (Ueno, Inada, Saeki, & Tsuji, 2006a; Ueno, Sano, Saeki, & Tsuji, 2006b). Similarly, Vassileva et al. (2012) found that using an interactive web page to display household consumption feedback achieved a 15% reduction in electricity consumption from those households that visited the web page at least once (Vassileva, et al., 2012).

Electricity price, participation level of customers, as well as incentive and penalty values are other factors that affect the level of power consumption in households (Moghaddam, Abdollahi, & Rashidinejad, 2011). Dynamic electricity pricing is a DR technique that is normally used to reduce peak demand on the electric power grid (Avci, Erkoc, Rahmani, & Asfour, 2013; Ericson, 2011; Gyamfi, Krumdieck, & Urmee, 2013). A dynamic tariff is designed such that the price per unit ($/kWh) of electricity consumed is higher at times when the load on the system is at a peak and the price per unit ($/kWh) is lower during the off-peak hours. Consumers tend to shift their peak load from the periods of high tariffs to times when the tariff is lower, while maintaining the same total energy consumption. The impacts of dynamic electricity pricing on price spikes, peak demand, consumer energy bills, power supplier profits and congestion costs have been explored by Valenzuela et al. (2012), with the help of an agent-based model known as Electricity Market Complex Adaptive System or EMCAS. The model provides consumers with day-ahead forecasts of peak and off-peak prices in an attempt to influence customers to use energy at different times of the day (Valenzuela, Thimmapuram, & Kim, 2012).

2.6.1 Demand response programs

Demand Response Programs can be classified into two main categories, namely: incentive based programs (IBP) and price based programs (PBP) / time based programs (TBP) (Aalami, Moghaddam, & Yousefi, 2010a, 2010b; Albadi & El-Saadany, 2008).

2.6.1.1 Incentive based programs (IBP) include:

- Direct load control programs

In direct load control (DLC) programs, the utility or system operator has the ability to shut down or cycle the power supply to a customer's appliance remotely, on short notice, for a short period of time. Most appliances that are shut down or cycled are ones that consume high levels of power. Typically, remotely controlled appliances in developed countries include air conditioners, water heaters and swimming pool pumps. One such program in the USA achieved a total demand reduction of 1000MW during normal conditions and 2000MW during emergency condition (Ericson, 2009; Strbac, 2008).

- Interruptible/Curtailable programs

With Interruptible/Curtailable (I/C) programs, the participants receive upfront incentive payments, bill credits or rate discounts. Participants are asked to curtail a specific block of electric load or curtail their consumption to a predefined level during system contingencies. Customers should typically respond within $30-60$ minutes of being notified by the utility. If the participants do not respond, they can face penalties, depending on the program terms and conditions. The number of times or hours that such interruptions can be called by the utility provider is limited to not more than 200 hours per year (Aalami, et al., 2010b).

- Demand bidding programs

In demand bidding (DB) programs, customers bid on the price at which they are willing to offer a specific load reduction or identify the amount of load they are willing to curtail for a given price. Once a bid is accepted, customers can face penalties if they do not curtail the load by the amount specified in the bid. This type of program helps to maintain a steady supply and demand without having to increase the generation capacity. Some techniques that are currently used include programmable thermostats to control air conditioning and heating systems (Grover & Pretorius, 2007; Strbac, 2008).

- Emergency demand response programs

Emergency demand response programs (EDRP) provide incentives for the amount of load customers curtail during emergency conditions. But in this case, the curtailment is voluntary (Nikzad & Mozafari, 2014).

- Capacity market programs

  Capacity market programs (CAP) are offered to customers who can commit to providing pre-scheduled load reductions when system contingencies arise. Customers usually receive a day-ahead notice of events and are penalized if they do not respond when directed.

- Ancillary services market programs

  Ancillary services (A/S) market programs allow customers to bid on load curtailment in the electricity market as operating reserve. If the bids are accepted, customers are paid the spot market price for committing to be on standby. If load curtailments are required, they are paid the spot market energy price for doing so (Partovi, Nikzad, Mozafari, & Ranjbar, 2011).

2.6.1.2 Price based programs (PBP) or Time based programs (TBP) include:

- Time of use pricing

  Time of use (TOU) pricing programs are the basic type of PBP. These programs use any rate scheme that differs according to different blocks of time, whether by time of day or by season. The rate during peak periods is higher than the rate during off-peak periods. The simplest TOU rate has two time blocks: the on-peak period and the off-peak period (Gellings & Chamberlin, 1993; Tishler & Ye, 1993). The cost effectiveness of this program generally depends on three factors: the utilization amount of different customers, tariff characteristics such as the ratio of peak to off-peak prices and the length of the peak period, and the nature of the peak load (Hill, 1991). These pricing schemes are a key approach to DSM in most countries, and so they are widely used. Significant amounts of reduction in peak power and energy shortages have been achieved by the use of this tariff structure in a number of utilities (Shaikh & Dharme, 2009; Strbac, 2008).

- Critical peak pricing

Critical peak pricing (CPP) rates use a pre-specified price for higher electricity overlaid on TOU rates or normal flat rates. These are used during contingencies or when market conditions meet a pre-defined criteria, for a limited number of days or hours per year (Jazayeri et al., 2005). Customers participating in these programs are informed about the increase in price a day prior to the action. Empirical evidence for the efficacy of CPP can be found in a research conducted in California by (Herter, 2007). Herter observed an average 41% reduction in load was achieved over two hour hot-water CPP events when households were provided with sophisticated end-use controls. It was also observed that without the end-use controls, an average 13% reduction in load was achieved over five hour hot-water CPP events. A study by Faruqui and Sergici (2010) also supported this data. In the range of experiments they discussed, the CPP tariffs encouraged a drop in peak demand that ranged 13%−20%. When accompanied with enabling technologies, the reduction in peak demand is in the range of 27%− 44% (Faruqui & Sergici, 2010).

- Extreme day pricing

Extreme day pricing (EDP) programs are similar to CPP except that the higher price for electricity is in effect for the whole 24 hours of the maximum number of critical days, which are known a day ahead.

- Extreme day critical peak pricing

Extreme day critical peak pricing (EDCPP) is a variation of CPP in the sense that, CPP rates for peak and off-peak hours apply during extreme days, but there is no TOU pricing on the remaining days of the year.

- Real-time pricing

Real-time pricing (RTP) programs are programs in which the utility's actual electrical power demand and energy costs are continuously reflected in the pricing rate structure. Customers are charged depending on the actual cost of electricity on the wholesale market and prices fluctuate on an hourly basis. Customers are informed about the rates on a day-ahead or hour-ahead basis. Special metering systems can be used for reporting the customer usage and costs in either real-time or on an as-requested basis. Customers plan their consumption for the day depending on the daily forecasts of hourly electricity prices provided to them by the utility (Aalami, et al., 2010a; Albadi & El-Saadany, 2008; Gellings & Chamberlin, 1993). In economic terms, real-time pricing shifts the demand from the peak periods and makes the demand price more elastic, and therefore, more balancing, with fewer supply-side adjustments.

2.6.2 Advantages of using demand response programs

The improved resource-efficiency resulting from greater interaction between power consumers and their suppliers can be considered the biggest advantage of demand response programs. The overall benefits of demand response can be categorized into the following four groups.

- Participant financial benefits

  All those who participate in the DR programs receive savings on their electric bill if they use less electric power during the peak periods. Customers participating in classical IBP programs can receive incentive payments for their participation, while those participating in the market-based IBP programs can receive payments according to their performance (Jazayeri, et al., 2005; USDOE, 2006).

- Market-wide financial benefits

  Due to the efficient utilization of electric power as a result of DR programs, a market-wide price reduction of electricity can be expected. This also results in lower demand for more costly power generation. Since the power can be utilized in a more efficient way, the cost of upgrades in the transmission and distribution infrastructure can be avoided. In turn, this can be reflected in the cost of electricity (USDOE, 2006).

- Reliability benefits

  The risk of power outages can be minimized by implementing a well designed DR program. By participating in these DR programs customers are able to minimize their own risk of having power interruptions or outages. These programs also provide more options and resources for the system operator to maintain the reliability of the system (Affonso & Silva, 2010; Goel, Qiuwei, Peng, & Yi, 2005).

- Market performance benefits

  Customers participating in DR programs have more choices in the market, even if there is no retail competition. Participants are able to manage their own usage since they have the opportunity to affect the market especially with the market-based programs and dynamic pricing programs. This has been the main driver for the DR programs, especially for large consumers, for a lot of the utilities. DR minimizes the ability of the main market players to exercise power in the electricity market. During the 2000−2001 California electricity crisis, it was reported that a 5% demand reduction could have resulted in a price reduction of 50%. This can be expected because the generation cost increases exponentially near maximum generation capacity. Hence, a huge reduction in generation cost can be achieved by a small reduction in the demand (Spees & Lave, 2007).

2.6.3 Voluntary demand response

Voluntary demand response (VDR) involves the end-user's participation in changing the amount of energy used by changing normal behavior patterns in order to achieve goals the end-user thinks are important. The power supplier provides information about the operation of the system to improve understanding of how end-use behavior impacts different factors, including carbon emissions, price and security of supply. VDR is a developing area of study with limited literature available on its application.

A study carried out in Christchurch, New Zealand, indicated that as much as 10% of morning peak load and 7% of evening peak load was volunteered for attenuation after learning about the distribution constraint and subsequent need for diesel generation on the otherwise exclusively hydro powered grid (Gyamfi & Krumdieck, 2011). One of the strongest VDR factors identified in this study was concern that high demand on a constrained grid could cause brown-outs or black-outs. The cost-benefit analysis of VDR carried out by comparing the investment cost of the DR program with the avoided transmission and distribution investment cost showed that the project could pay for itself after four years (Gyamfi & Krumdieck, 2012). The results of the Eco-living Program carried out in Singapore indicates that a combined use of leaflets and stickers to create awareness amongst consumers can reduce the average consumption by as much as 15.8% (He & Kua, 2013).

2.7 Energy audit and energy survey

The accuracy of an energy analysis depends on the amount of data that can be obtained and analyzed. Sufficient data for analysis can be obtained by carrying out an energy audit along with a detailed energy survey. This section describes how an energy audit and energy survey of a remote island energy system can be carried out.

2.7.1 Energy audit

An energy audit is an excellent tool for finding operational and equipment improvements that will conserve energy and minimize energy costs (Escrivá-Escrivá, Santamaria-Orts, & Mugarra-Llopis, 2012). It is a key tool in providing a systematic approach for decision making in the management of energy. In a broader perspective, an energy audit can be defined as a process to evaluate where energy is being consumed within a building or any other facility. It can identify the opportunities available for energy conservation (Capeheart & Spiller, 2004; Dall'O', Speccher, & Bruni, 2012; Shen, Price, & Lu, 2012). Energy audits are subdivided in to three basic types or levels (Thumann & Younger, 2008).

Level 1 - "Walk-through Audit"

This is the basic starting point for any energy optimization process. It is a simple visual inspection of all the energy using systems in-order to obtain the general information. The process doesn't require many resources and is the least expensive level of auditing.

A walkthrough energy audit was conducted by (Saidur, Rahim et al. 2009) on 91 factories in the industrial sector of Peninsula Malaysia (Saidur et al., 2009). Their research highlighted four important steps that need to be carried out while conducting a walk-through energy audit.

1. Conduct a meeting with appropriate personnel to identify the areas where the auditors' attention should be focused during the audit.

2. Prepare a questionnaire and a checklist.

3. Send the questionnaire and the checklist to the place being audited atleast one week prior to the audit in order to allow sufficient time for the relevant person to get organized.

4. Form an energy audit team and train them in order to conduct the walkthrough energy audit. Each audit team should be accompanied by an expert auditor.

The most important feature of a walkthrough energy audit is that it creates a benchmark which can be later utilized by other sources for future analysis or study purposes (Saidur, et al., 2009; Zhu, 2006). A level-2 standard audit requires this benchmarking in order to carry out the detailed analysis of the facility.

Level 2 - "Standard or General Audit"

A Level 2 audit starts with the findings of the walk-through audit, and further evaluates the energy systems in detail. The standard or general audit will lead to the identification of potential energy efficiency improvements and significant conservation opportunities.

A standard audit requires data on energy usage profiles, utility bills and additional metering of any specific energy consuming systems (Kabir, Abubakar, & El-Nafaty, 2010). Detailed interviews with operating personnel are carried out for a better understanding of the systems. The Level 2 audit results in recommendations for improving the efficiency of operation and maintenance, as well as for hardware changes (Alajmi, 2012).

Level 3 - "Computer Simulation"

This level of audit is a much more complex process where computer programs are used to accurately model the complete energy system. They model how the system would respond to changes or variations in energy flow, and evaluate how the efficiency of the system could be improved. A Level 3 audit requires much more resources and finance for it to be carried out. It involves a lot of detailed data collection over the course of weeks, months or years.

An energy audit for a remote island requires adapting the standard methods to a village-scale level. Historical network load data and information characterizing the power supply system needs to be collected from the local operators and the utility. A Level-1 audit can be performed in order to acquire a rapid assessment of the island's energy system. Then, a detailed Level-2 audit requiring detailed survey questionnaires can be carried out. For a remote island energy system, a Level-3 audit can be avoided to minimize the complications of both resource and financial barriers.

2.7.2 Energy survey

In general, a survey can be defined as a method for gathering information through "a voluntary encounter between strangers in which an interviewer seeks information from a respondent by engaging in a special type of conversation" (Peck & Devore, 2011). It can be either a self-administered questionnaire or an interview carried out in person. An energy survey is carried out to collect information required about the status of energy being consumed and also to identify the possibilities for improving the energy efficiency in a particular facility (X. Zhou, Yan, Zhu, & Cai, 2013). To improve energy efficiency is to get more work done from a known amount of input energy. Surveys also help in putting energy conservation measures into place and understanding the challenges of their implementation.

An energy survey is almost always carried out along with an energy audit in order to obtain additional information about the energy system being audited. Surveys can acquire more critical information of the system through the experiences of the people using that system. This helps in formulating a more descriptive audit report and hence a detailed model of the energy system.

Energy consumption surveys of residential buildings have been carried out along with energy audits since the 1980s in England (Yannas, 1996) and the United States (Ural, 1980 (a), 1980 (b)). Similarly, they have been carried out in Greece (Santamouris, Balaras, Dascalaki, Argiriou, & Gaglia, 1996; Trianti-Stourna et al., 1998), India

(Thomas, Natarajan, & Anand, 1991) and also in China (Weiding, Yiqun, Cunyang, Lei, & Xin, 1998; Welding, 1996).

2.8 Energy modelling

There are various techniques used for the modeling of energy consumption. But almost all of them fit in to one of two main approaches: top-down approach and bottom-up approach. These two approaches differ in both the level of input information as well as in their calculation or simulation techniques. The amount of data available is a major factor for the modeling technique, because the end result of the calculation or simulation will entirely depend on the input data.

Input data required for modeling residential demand response includes information about the occupants and the appliances used, historical energy consumption data, the physical characteristics of the dwelling and the climate conditions (Capasso, Grattieri, Lamedica, & Prudenzi, 1994). The basic method of information collection is through energy audits and energy surveys. Climate condition data and historical energy consumption data is mostly logged by the authorities concerned.

2.8.1 Top-down approach

Top-down models examine the broader economy and are characterized by behavioral relations on an aggregated level. They do not distinguish energy consumption due to individual end-uses, and technological details are not typically provided by these models. Variables such as macroeconomic indicators (e.g. Gross Domestic Product (GDP)) and climate conditions are commonly used by top-down modeling (Böhringer & Rutherford, 2009).

Saha and Stephenson (1980) developed a similar model for New Zealand, although it had a technological focus. In this model, space heating, hot water system and cooking loads are analyzed separately and then added to calculate the total consumption. The annual energy consumption of each fuel used to support each end-use group as a function of stock, ownership, appliance ratings and use was determined by the energy balance equation

$$E_{an,e,f} = S \,.\, C_{e,f} \,.\, R_{e,f} \,.\, U_{e,f} \qquad \textbf{Eq. 2}$$

where E is the annual energy consumption of end-use group e, corresponding to fuel type, f. S is the level of applicable housing stock, C is the appliance ownership level, R is the rating of all appliances within an end-use group and U is a use factor. The resulting predictions of this model using the historical data from 1960s and 1970s were very accurate (Saha & Stephenson, 1980).

2.8.2 Bottom-up approach

Bottom-up models describe current and prospective technologies in detail and have been used within energy analysis and planning (Klinge Jacobsen, 1998). This type of modeling approach can be used for either optimization or simulation since it consists of a high level of detail. Common input data for this type of modeling approach includes equipment details and usage schedules, occupants' schedules and dwelling properties (Capasso, et al., 1994).

In a study by Parti and Parti (1980), researchers attempted to determine the level of use of individual appliances based on bottom-up regression methods using the data of 5,000 households and their corresponding monthly billing data. A conditional demand equation, which was based on the indication of appliance ownership and other demographic factors gathered from a survey, was proposed. The monthly regression equation that was proposed is

$$E_{mo} = \sum_{i=0}^{N} \sum_{j=0}^{M} b_{ij}(V_j A_i) \qquad \textbf{Eq. 3}$$

where E_{mo} is the monthly electrical energy consumption, V is a variable indicating appliance presence or count for appliances, j, A is a set of interaction variables with elements, i, such as the number of occupants, income, and floor area, and b is a coefficient of the j^{th} exogenous variable in the i^{th} conditional demand function. In the proposed equation, V_o and A_o are taken as unity to account for appliances whose presence were not surveyed and for appliance energy consumption unrelated to interactions with other surveyed information (Parti & Parti, 1980).

(Richardson, Thomson, Infield, & Clifford, 2010) suggested the model shown in Figure 2.4 as an architecture of an electricity demand model. In this model the appliances such as TVs, stoves or washing machines, are the basic building blocks. Active occupancy data represents the data related to the amount of people who are present and awake, at the dwelling. Daily activity profiles contain the data that represents the activity being undertaken with respect to the time. This data varies for every specific activity and is a function of the active occupancy. The list of installed appliances contains data on the number of particular appliances installed in a specific dwelling. The power characteristics represent the data including the details of a particular appliance's behavior when it is in the on or off position. Some appliances are considered off when they are in standby position, and hence these appliances will be taken to consume some power when in the off position.

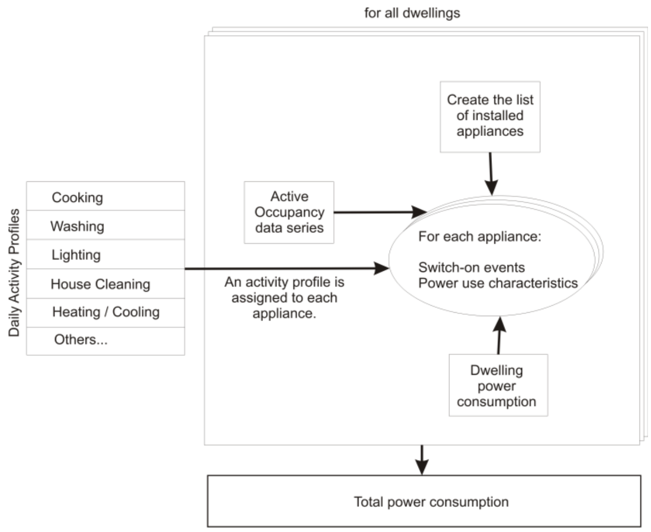


Figure 2.4: Architecture of an electricity demand model

(Source: Richardson, Thomson et. al. 2010)

2.8.3 Method of diversified demand

The method of diversified demand was developed by Arvidson in the year 1940 to estimate the load on distribution transformers when measurements of the actual load were limited. According to the diversified demand methodology, "if the location can, in aggregate, be considered statistically representative of the residential customers as a whole, a load curve for the entire residential class of customers can be prepared" (Gönen, 1986). This method is based on the fact that all the electrical appliances available in any household may not be used at the same time or to their full capacity. It is also based on the fact that not all households in a group or community use the same appliance at the same time. In other words, the method takes into account the diversity in utilization between similar loads and non-coincident peaks of different types of loads.

Arvidson also introduced the hourly variation factor (HVF) in order to account for the non-coincident peaks of different types of loads. The HVF is defined as "the ratio of the demand of a particular type of load coincident with the group maximum demand to the maximum demand of that particular type of load" (Gönen, 1986). According to the definition, HVF is a value that represents the behavioral characteristics of a particular appliance's usage with respect to time, and may vary from one community to the other (Gyamfi, Krumdieck, & Brackney, 2010). An example of HVF is presented in Appendix A1, which shows the HVF calculated by (Gönen, 1986) for different household items.

The following are definitions that need to be understood in order to proceed with the method of diversified demand.

Maximum demand (MD) - This is the maximum load that is observed during a given period of time.

Diversified demand - This is the total load of the composite group of unrelated loads observed during a given period of time.

Maximum diversified demand (MDD) - This is the maximum sum of the contributions of the individual demands to the diversified demand over a given period of time.

Appliance saturation rate - This is the ratio of the number of households having at least one of the given appliances to the total number of households in consideration.

The general equation for calculation of the MDD is

$$MDD(t) = \sum_{i=1}^{p} GMD_i(t) \qquad \textbf{Eq. 4}$$

where *MDD* is the maximum diversified demand at time *t*, *i* is the appliance category, *p* is the total number of appliance categories and GMD_i is the group maximum demand of appliance category *i* at time *t*, which is calculated by

$$GMD_i(t) = MD_i \times F_i(t)$$ **Eq. 5**

and,

$$MD_i = ADD_i \times A_i$$ **Eq. 6**

and,

$$A_i = C \times s_i$$ **Eq. 7**

where MD_i is the maximum demand of the appliance category i, F_i is the hourly variation factor of the appliance category i, A_i is the total number of appliances in the category i, C is the total number of households in the community and s_i is the appliance saturation rate. ADD_i is the average diversified demand per customer for an appliance in the category i.

The value of *ADD* depends on the total number of appliances *A*. The average diversified demand (ADD) decreases with an increase in the number of appliances (*A*), until *ADD* becomes a constant at larger *A* values. Table 2.2 shows how *ADD* varies with an increase in *A*, for some household appliances. Appendix A2 shows how *ADD* varies with *A* for various residential loads (Gönen, 1986).

Table 0.1: Average diversified demand per customer (in kW) for different number of appliances

Load type	**A = 1**	**A = 5**	**A = 10**	**A = 20**	**A = 40**	**A = 60**	**A = 80**	**A = 100**
Refrigerator	0.180	0.071	0.060	0.052	0.049	0.048	0.048	0.048
Range	2.300	0.880	0.700	0.620	0.580	0.560	0.550	0.550
Lighting and Misc	1.100	0.640	0.580	0.550	0.540	0.540	0.540	0.540
Air conditioner	4.600	3.100	3.000	2.900	2.900	2.800	2.800	2.800
Home freezer	0.300	0.130	0.100	0.090	0.080	0.080	0.080	0.080

This method can be utilized to calculate the total demand of a community by individually calculating the diversified demands for the three categories given in **section 2.4**, and then aggregating them to get the maximum diversified demand.

2.9 Summary

A critical review of literature on remote area power supply (RAPS) systems and the different control strategies being used to manage the energy demand in these systems was presented in this chapter. It was highlighted that maintaining a secure and reliable power supply in RAPS is a major challenge for the utility industry. The most feasible method for power supply in these areas is to generate the power locally, which is normally achieved with the help of a diesel generator. However, in the face of fluctuations in fuel prices, installing a hybrid energy system has proved to be the most economical mode of power generation for RAPS systems.

This chapter also highlighted the control strategies utilized in RAPS systems. Control strategies such as power availability schedules and rolling blackouts have been incorporated into communities to manage power supply side complications.

The more recent smart grid technology used in the electrical utility sector was also discussed in the chapter. Available literature on smart grids was reviewed and the four main components that make up a smart grid were explained.

An explanation of how the end-use load can be characterized in order to carry out demand side management techniques effectively was presented in this chapter. The three main classifications of end-use demand described in this chapter are important steps for the methodology contributed by this thesis. The chapter has highlighted how behavioural psychology has been exploring the field of energy consumption behavior. It was found that peoples' attitudes, beliefs and motivations are critical factors contributing to energy consumption behavior.

A comprehensive review on demand side management techniques was also presented in this chapter. Different demand response programs (DRP) including incentive and price based programs, were discussed along with the advantages of using DRP in the utility sector. The concept of voluntary demand response (VDR) was also presented and the literature so far has shown that when providing consumers with information on how their behavior impacts factors such as carbon emissions, price and security of supply, they tend to reduce the amount of energy they use. However, VDR is a developing area of study with limited literature available on its application.

A review of the literature on energy auditing and energy surveying was presented and explained in order to determine an appropriate method to be used for this research. It was found that for a remote island, it is required to adapt the standard methods to a village-scale level. Research has shown that both Level-1 and Level-2 energy audits need to be carried out to acquire an assessment of the island energy system. While a more complicated Level-3 energy audit can be avoided in these areas, a general energy survey can be conducted along with the energy audit to obtain additional detail about the energy system.

Different energy modelling techniques being utilized by the utility sector have been discussed, including the method of diversified demand, which is used throughout this research for load calculation purposes.

An understanding of the published work discussed in this chapter was crucial for the author to make decisions regarding the development of a novel methodology for demand management in remote communities that is presented in the next few chapters. Detailed theory on this novel methodology is provided in Chapter 3.

Chapter 3

Theory of Participatory Demand Response

"A man's value to the community primarily depends on how far his feelings, thoughts, and actions are directed towards promoting the good of his fellows"

-Albert Einstein-

AFTER reviewing the literature on the field of remote area power supply (RAPS) systems and demand response (DR) technologies in the past chapter, this chapter covers the theory of Participatory Demand Response (PDR). An explanation of the concept of PDR and its design concepts is provided. Section 3.1 is an introduction to PDR. Section 3.2 is a theoretical background on the basic concept behind PDR. Section 3.3 concentrates on the design of the system. This section illustrates the difference between traditional open flow control systems and the proposed feedback controlled system model. Section 3.4 discusses the voluntary participation potential levels utilized in the system, and section 3.5 explains the reference elements of the PDR model. Finally section 3.6 provides a summary of the chapter.

3.1 Introduction

The previous DSM studies were carried out for large utilities on national grid networks. Participatory demand response (PDR) proposes a new idea that people can understand the way their power supply system works and voluntarily participate in using power in certain ways to keep costs in check, rather than simply responding to price rises. PDR can have the same effect as DSM with peak clipping or load shifting, but the main mechanism used to achieve the improved security and operational efficiency would be shared information from the utility operator. The PDR program would be designed to function as a feedback control signal. In this regard, the customers are seen as providing diffuse control of the electricity system through choice of activities and appliances use (Krumdieck & Hamm, 2009). In order to design a PDR program, the end-use behavior would have to be ascertained by energy audits, and the realization of security and sustainability values of the community would have to be understood through surveys. The customers can exert effective control if they have appropriate knowledge about the energy system and relevant real-time information when the system performance is not within the design or operational reference values.

The PDR program differs from other types of DR techniques mainly in its approach. PDR is a coordinated development and management technique that utilizes the cooperative behavior of the entire community to achieve quality of life objectives. This helps to maximize the economic and social welfare of the community in an equitable and sustainable manner.

3.2 Basic concept behind PDR

The basic concept behind PDR is based on Krumdieck's theoretical model of regional energy systems (Krumdieck, 2007). Designing and operating a regional energy system from the component-level perspective may be sufficient as long as the system capacity significantly exceeds the demand. Krumdieck argues that even though a grossly over-designed system may be reliable, it is not an efficient use of available resources. In order to efficiently design a viable regional energy system, limitations in available resources and environmental constraints need to be incorporated into the relationship between suppliers and consumers. The general form of Krumdieck's theoretical model of a regional energy system is shown in Figure 3.1. It has been defined as:

> *"any community of people, their relationships with each other through economic activities, the infrastructure that they use in these activities, including appliances, buildings, etc. within a given environment and resource setting." (Krumdieck, 2007)*

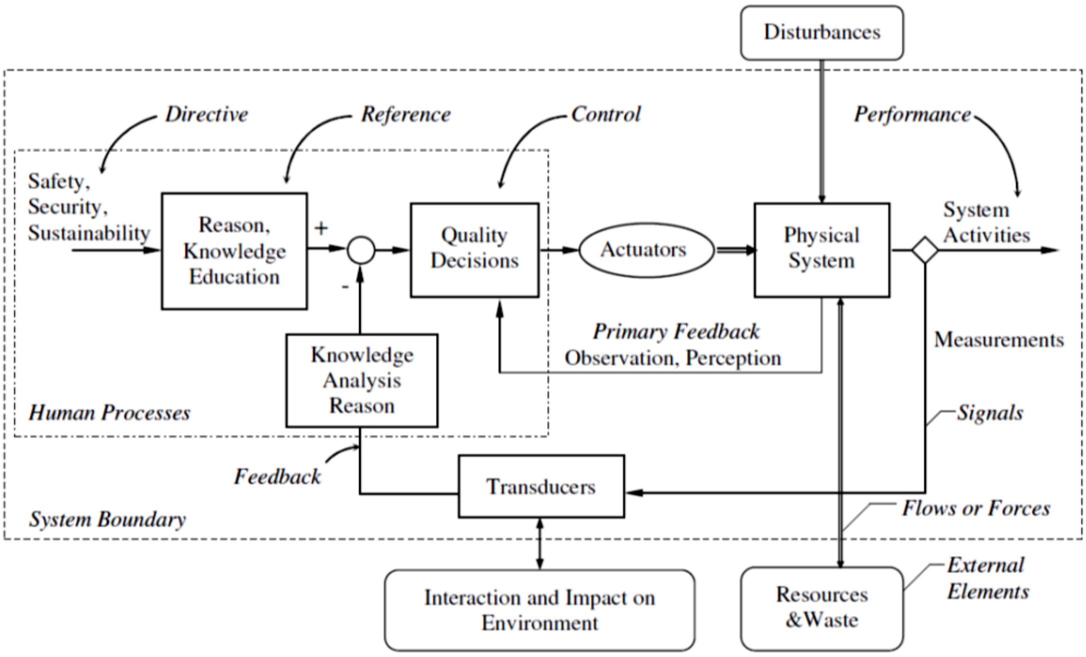


Figure 3.1: Krumdieck's regional energy-environment-economy system model

(Source: (Krumdieck 2007))

Krumdieck's model is a representation of the dynamics of the systems. Therefore, any changes in the technology, built environment or resources would require an adaptation of the dynamic model to describe the new system. The important terminologies used to describe the system are explained below.

Directive - This depends on the cultural values and the shared vision of the society. Perhaps it could be best described as the aspiration of the people to satisfy their various requirements. Safety, security and sustainability can be considered the most predominant needs for a healthier regional energy system.

Reference Elements - this signifies the sustainable levels of resource consumption and environmental impacts of a society carrying out their nominal activities. It could be described as the level of knowledge, education and reasoning a society already acquires on the current energy system.

> *"In other words, determining a sustainable, safe and secure level of consumption, and impacts to support a certain level of activity would require a concept level system model for a specific region employing some specified set of technologies" (Krumdieck, 2007).*

Feedback Elements - Two main feedback signals have been designated in the regional energy system model: the primary feedback signal and the general feedback signal. The primary feedback signal is used directly and continuously by all of the people in order to function effectively. The observations and knowledge people have gained from daily experience are included in the primary feedback. This feedback is considered a crucial source of information for system control due to its direct relation to particular activities. Whereas general feedback does not usually include information that is directly related to or observable by individuals, this feedback normally includes the information about the aggregate impact of activities on the environment.

Comparator - The comparator offers continuous output on the difference between the feedback of actual measured data and its impacts against the reference levels. In general terms, the comparator continuously evaluates the system by subtracting the feedback signal from the reference signal. For example, in pre-industrial societies, traditional knowledge on how to maintain daily activities in a sustainable manner would have been a strong, shared cultural vision. As a consequence, people would have observed and understood the impact their actions had on the local resources they depended on for survival.

Control Elements - Depending on the system performance with respect to the reference, the controller triggers the necessary changes to the actuating elements which are required to neutralize the problem. In Krumdieck's model, the controller is an aggregate of daily decisions made by individuals or groups in order to maximize the quality of life.

Actuating Elements - These represent the economic status and the lifestyle of the society. It is through economy that people access facilities when particular decisions are made. For example, when a decision is made that cooling is required in warmer climates, people access those facilities according to their economical standard.

Forward Elements - This is the physical system. It represents everything in the built environment that the community utilizes in their everyday life. This includes, for example, the power generation technology, transmission and distribution system, and the appliances that are being utilized.

Flows across the system boundary - These represent the material inputs into the built environment and the wastes emitted into the natural environment.

Disturbances - These physically bring about a change in the built environment. Even if the changes are positive in effect, such as developments in technology and innovation, they are an external disturbance to the existing system.

This thesis uses Krumdieck's theoretical model of regional energy systems as a base in order to design a feedback control strategy for remote power systems that incorporates the behavior of the community to achieve a sustainable, reliable and secure energy system.

3.3 Design of the PDR system

Participatory demand response involves engaging stakeholders, including the public and the energy suppliers, in a cooperative effort to manage the electrical energy system by incorporating community knowledge and values into a feedback control system. A fundamental key to success with this system is community involvement in setting goals and understanding the limitations of the system.

3.3.1 Traditional model of electric power generation

The traditional electric power generation system was designed as an open flow electricity system without accounting for the values, knowledge or priorities of the community. There is no constructive communication between the supplier and the customer regarding the difficulties in the system as a whole. Figure 3.2 shows the general control diagram of the traditional open flow system.

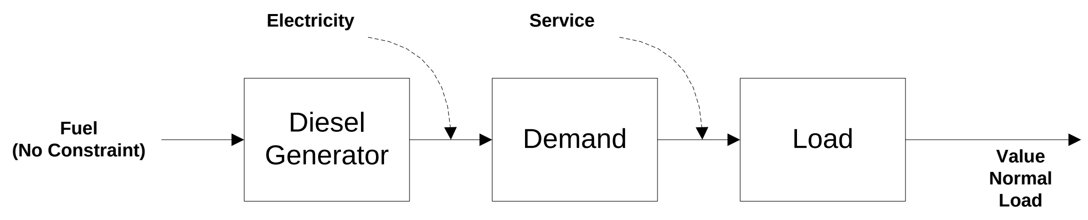


Figure 3.2: Traditional open flow electricity system

A major disadvantage of the traditional system is that the customer does not have a lot of knowledge about supplier side complications. There are no restrictions to the demand side, which puts the supplier in a position of having to keep up with fluctuations in the load. As a consequence, the complete electrical system becomes complex and difficult to maintain. The ultimate result is a decrease in security and reliability.

The shift towards a more cooperative and integrated planning process is a crucial method in avoiding potential misunderstanding in the management of a healthier electrical system. As explained in **section 3.1**, the PDR methodology helps to close the gap between the supplier and the customer, making it a more informed system. In the PDR embedded system, people will act in their own best interests by changing their normal end-use behavior in order to maintain a secure and a reliable power system.

3.3.2 Participatory demand response system model

The PDR methodology adopts Krumdieck's regional energy system model to describe its control system. Figure 3.3 shows the model for the PDR feedback control system. The directives of the system are to maintain a sustainable, secure and reliable electrical energy system that can absorb disturbances from the environment and adjust accordingly. For processing such controls, the system has to have strong reference elements. In this case, people need to have firm knowledge of how the PDR system works, the reason why each step is important and they need to know how to manage their lifestyle activities in order to achieve the system directives. A detailed explanation of the reference elements is given in **section 3.5**.

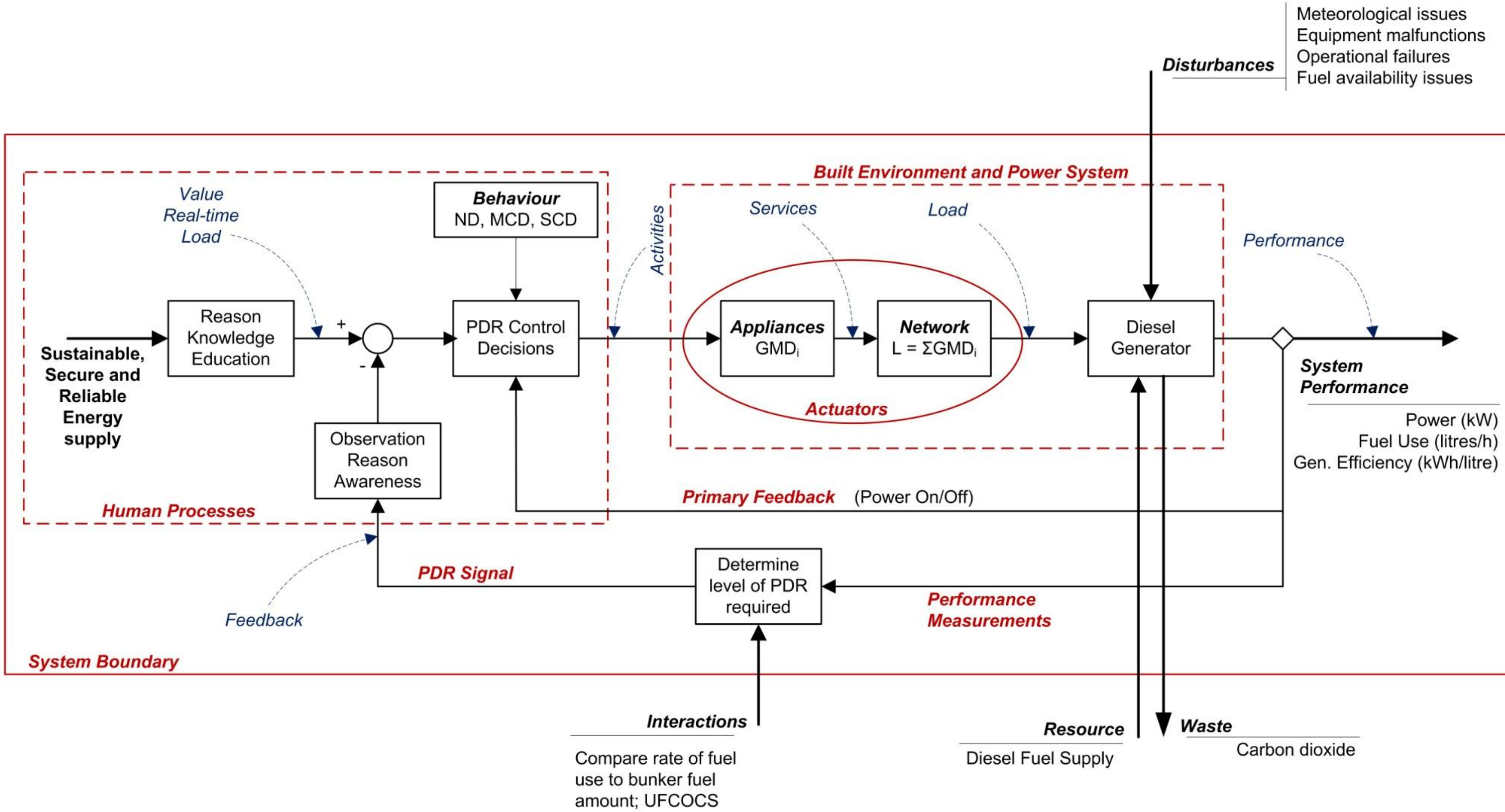


Figure 3.3: PDR feedback control system model

The feedback of the PDR system is divided in to two main signals: the primary feedback and the general feedback. The primary feedback depends on the physical observations made by all of the stakeholders. An example of a primary feedback in a remote community can be the arrival of a fuel shipment. This can be a well known event that can trigger a feedback signal to continue with the normal load, if there was a constraint in effect. Similarly, for the supplier, a primary feedback can be to introduce a constraint situation if one of the generators shuts down. This constraint situation is generated to maintain a secure power grid without load shedding, while operating a smaller generator in a high load period.

The general feedback is the information provided by the supplier about the situation of the power grid and the generation system conditions. This feedback needs to include information about the role customer cooperation plays and what needs to happen, in order to achieve a properly functioning energy system. Specific information such as a reduction in power consumption due to system constraints is also included in this feedback. In a remote community, general feedback can be displayed in places where community members can access it daily, for example at community centre, religious centres, outside the powerhouse or on a school notice board.

The set points of the PDR system have to be obtained after discussions between stakeholders. Engaging participants in the goal setting process as early as possible will allow the possibility of substantially improving the resultant model. This involvement of the participants can also result in an increase in knowledge and education potential for the public. In the PDR system, the set points are considered as set behavioral standards. In other words, this is what the consumers agree to practice, while carrying out their daily activities, in case of a constraint in the energy system. The PDR system developed in this research classifies the set points into three levels of participation and is defined as the Voluntary Participation Potential (VPP) of the end-users. VPP is further explained in **section 3.4**.

The VPP details, along with the real-time system load and the feedback signals, are used by the control elements to process the level of participation required from the community. The PDR control decisions reflect the level of constraint that is being faced by the system. Daily routine activities of the community are controlled depending on the PDR signal generated. The control signal being utilized by the system has to be finalized during discussion sessions amongst stakeholders, and consumers must be well aware of the actions to be carried out in regard to the signal generated.

The PDR control signal is fed into the actuating element which is one of the main components of the dynamic built environment. The actuating element includes services carried out by the customers. The use of appliances depends on the level of VPP agreed to by the stakeholders during constraint situations. The total load on the electrical power grid is the sum of all the GMDs of the appliance categories utilized by the community and is represented by **Eq.4**.

The second component of the dynamic built environment is the power source. In most remote areas, these power sources are the diesel generators. The performance of a generator depends on several external factors apart from the load on it. These factors include the following types of disturbances.

- *Meteorological issues* - Meteorological issues such as severe weather conditions can disrupt the delivery of fuel in standalone diesel systems. In hybrid systems, they can disrupt the availability of renewable energy resources such as solar radiation.

- *Equipment malfunction* - A malfunction in any piece of equipment related to power generation can lead to a major imbalance in the generating system unless it is attended to in an orderly manner that has been pre-planned.

- *Operational failures* - These disturbances are mostly the result of human errors. For example, not switching to a higher rated generator during peak load periods may lead to a system shutdown.

- *Fuel availability issues* - This is one of the main threats to an electrical power system. There are several factors which can lead to a decrease in fuel availability. Delivery issues, world market prices and political issues are some examples.

The output performance of the power source is measured and fed in to the feedback elements. The transducer in the feedback element converts the measured data into a digital signal for calculation purposes. In the feedback element, the measured rate of fuel consumption is compared to the bunker fuel amount in order to verify how long the available fuel will last. Depending on the results, the feedback element will determine the level of VPP required for maintaining a secure power system. If the fuel is being consumed at a rate that ensures stable generation of electricity until the next fuel shipment arrives, then the VPP level stays normal. Otherwise, a PDR signal will be generated where the level of VPP can be either medium or severe.

3.4 Voluntary participation potential

The reviews in **sections 2.3** and **2.5** showed that providing detailed feedback on energy consumption can trigger energy conserving behavior in end-users. The reviews also showed that consumers' intention and attitude are equally decisive factors in driving this behavior. For these reasons, in a PDR program, the consumers should not only be informed about their own consumption, but also about the status of the condition of power generation condition in the community. The consumers should be made aware of what actions need to be taken if there is a risk of loss of supply. In order to achieve the required energy management, cooperative participation of the end-users is required by the supplier. These actions can be represented as levels of constraint.

The levels of constraint represent the Voluntary Participation Potential (VPP) required from consumers to achieve an energy use target that limits load shedding. These constraint levels should be obtained by categorizing the loads into essentiality levels, which were explained in **section 2.4**., using energy audit and survey results together with, utility records.

A study by (Mohamed, Krumdieck, & Brackney, 2010) surveyed an island in the Maldives, and showed that the utilization of end-use load could be divided into three main levels of VPP depending on the severity of the supply constraint. These levels are *normal demand* (ND), *medium constrained demand* (MCD) and *severely constrained demand* (SCD).

Under the ND condition, residents carry out activities as usual. There is no communication or signal from the network operator. There are no limitations requested of residents on activities or appliance use. The rate of fuel being consumed in this condition remains below the maximum allowable consumption rate for a stable supply of electricity during the current fuel delivery cycle.

The MCD condition is the first level of VPP requested from the community. The load in this condition should be reduced from the ND condition enough to keep a reserve margin on the fuel supply until the next delivery. Under the MCD condition, general information is distributed to the community with a request to be conservative with energy use until a ND condition is declared or until the next fuel shipment arrives. In small, remote communities, the arrival of supply vessels is usually a well known event. The MCD signal could be announcements with suggestions for measures that families can take, based on the survey data. These could be given at schools, government offices or religious/community facilities.

The SCD condition is invoked in addition to the MCD condition and is specifically targeted at achieving deep reductions in overall load and managing load shapes to optimize the generation efficiency of the power supply. In this stage, the residents should turn off or do without some of their normal appliances such as air conditioners. They can be asked to curtail all non-essential energy use during certain times of the day. At this stage the load should be much lower than the ND condition. The main aim of the supplier should also be to minimize the amount of time consumers spend in this condition. A key strategy of the PDR program design is to target households with air conditioners or other large loads while executing the SCD condition.

3.5 Reference elements of the PDR model

The electrical energy system is considered to be a dynamic model. It involves complex human behavior integrated into the dynamics of the system. Incorporating feedback technologies into this dynamic energy system can assist in reducing the level of complexity. The feedback supplied to the energy consumer must inspire energy conservation behavior. However, there are three main elements that have to be considered for this feedback controlled energy system to work. In the PDR feedback control model, these three elements are considered as the three reference elements.

3.5.1 Knowledge

Knowledge is a critical resource that provides a sustainable competitive advantage in a dynamic system (Davenport & Prusak, 2000). Exchange of knowledge between the stakeholders of a dynamic energy system is a fundamental key for a sustainable performance. Knowledge is not just exchange of information; it is information which is justified by one's belief and know-how (Nonaka, 1994). Therefore, knowledge can be considered as information that is processed by an individual which includes ideas, facts, skills and judgements. It can be relevant for an individual, a group or a community. A high level of knowledge gives individuals the ability to better manage resources and efficiently monitor the results (K. G. Smith, Collins, & Clark, 2005). It also helps them to better understand and absorb the information they are exposed to, and make it easier to compare the past and present routines (Cohen & Levinthal, 1990; Haleblian & Finkelstein, 1999).

The PDR methodology involves community participation rather than that of individual consumers. It requires the knowledge of community members as a collective contribution to build the feedback system. Gathering community knowledge is a dynamic process that involves interactions between the participants and the suppliers. Organizing a meeting between the stakeholders for joint activities and discussions on issues relating to the energy system and its operation is an important step. The objectives of the meeting should be to:

- increase knowledge sharing between the power suppliers and consumers
- understand the difficulties on both sides and discuss possible solutions
- understand how the PDR methodology works
- facilitate a liaison officer to convey routine developments
- finalize how the information will be conveyed

The final outcome of the PDR methodology highly depends on the level of knowledge exchanged between the stakeholders. As a consequence, this element is of the utmost importance. Good information needs to be ascertained, during the initial stages of implementation.

3.5.2 Reason

Reason can be defined as the capacity for consciously making sense by applying logic, for establishing and verifying facts, and justifying practices and beliefs based on new or existing information (Kompridis, 2000). The concept of reason is also referred to as human rationality. The reason for a particular human behaviour is justified by their motive or rational ground. This is explained by the fact that when people are unable to find or create a good reason to make a particular choice, they may delay action until a good reason becomes available (Luce, 1998).

A decision made often depends on the degree of convincing rationale, so that the reason for the decision can be explained to others (Shafir, Simonson, & Tversky, 1993). It is also made for personal motivation purposes, so that the decision made builds confidence of having made the right choice (Hausman & McPherson, 2006). In an energy system where human interaction has to be integrated in to it, the reasons for carrying out specific tasks at different stages, have to be clear for the participants. For a successful outcome from the PDR feedback system, the methodology adopted by the PDR system needs to be rationalized so that the participants are convinced to act appropriately. Most importantly, the participants must be very clear that the main reason for implementing the PDR methodology is to establish a reliable, secure and a sustainable electrical energy system in the community.

3.5.3 Education

Education has an imperative role to play in the development of a sustainable energy system. It is necessary for raising awareness of new technological and social developments. For a remote area, community education is essential in building confidence on a new system that needs to be implemented. It also enables the training of the public, which is necessary in order for the system to function effectively. Education enables the following activities that are important in achieving a resourceful feedback control energy system:

- promoting community awareness of the technology
- developing of consumer confidence in the technology
- training technical staff, who are essential in controlling the energy supply side

3.6 Summary

The main purpose of this chapter was to discuss the theory of participatory demand response and its design considerations. Development of applications for feedback controlled systems in the energy sector is an ongoing process involving researchers around the world. Nevertheless, Krumdieck's regional energy-environment-economy system model explained in **section 3.2** was found to be the most constructive energy system that could be adopted into a remote area power supply system.

The design of the participatory demand response system was discussed in **section 3.3**. The section presented the difference between the traditional open flow method of electricity distribution and the present feedback controlled demand response embedded electricity distribution system. The feedback controlled PDR model developed in this thesis adopts Krumdieck's regional energy system model to describe its control system. The three main reference elements governing the system are the knowledge, reason and education of the energy consumers found in the energy system. These reference elements were explained in **section 3.5**. The feedback of the PDR system was divided into two; the primary feedback and the general feedback. While the primary feedback depends on the physical observations of the stakeholders, the general feedback is the information provided by the supplier regarding system conditions.

The use of voluntary participation potential (VPP) levels was presented in **section 3.4**, along with the three levels of VPP: normal demand, medium constrained demand and severely constrained demand. The different levels of demand represent the amounts of energy that will be consumed by the end-users during varying levels of energy constraint. VPP levels are calculated using energy audits and energy surveys carried out in the community.

After illustration and explanation of the PDR model, an implementation procedure for the developed PDR model into a mini-grid was built. This implementation procedure is described in Chapter 4.

Chapter 4

Implementation of PDR Control in a Minigrid

"When people can see a vision and simultaneously recognize what can be done step by step in a concrete way to achieve it, they will begin to feel encouragement and enthusiasm instead of fright"

-Erich Fromm-

THE theory of participatory demand response (PDR) and PDR system design was presented in Chapter 3. An electrical power system was designed to incorporate human behavior such that PDR can be utilized to assist in resource constrained situations. This chapter provides a detailed description of the implementation procedure for introducing the developed PDR model into a remote mini-grid. Section 4.1, recalls the main points of the PDR control system and provides an introduction to the implementation process. Sections 4.2−4.5 explain the four main steps required for the implementation process. The graphical user interface (GUI) developed for the supplier side operation is discussed in section 4.6. Finally, section 4.7 summarizes the implementation procedure presented in the chapter.

4.1 Introduction

Control theory for PDR conveys that load is a result of activities and services, and that load can be controlled to match a target for a total amount of fuel consumed over a given time. The control system design depends on understanding the characteristics of the power supply system as well as the characteristics of the load. As described in **section 3.2.2**, in order to operate the feedback control system, the PDR to different control signals must also be understood.

The open flow control system illustrated in Figure 3.2 can be used to describe the energy flow when fuel is not a constraint. While the arrows represent the flows of fuel, electricity and end-use services, the blocks represent energy conversions. The output value indicated on the energy flow diagram encompasses the standard of living, productivity, enjoyment, comfort, convenience, etc. that was derived from carrying out activities using electrical energy services. People put a value on the activities they can carry out using electricity when it is lost due to a power supply disruption. People in remote communities have well adjusted ways of coping with power outages, such as doing washing or pumping water by hand, but the value people place on electricity provides the driver for operation and maintenance of the system.

In most remote systems, the price of electrical energy is subsidized and often charged at a flat monthly rate, or with modest ratcheted pricing that rises or falls according to usage or number and type of appliances. It has been observed that price has a rather weak effect on decisions about appliances or use of appliances in remote communities, other than household decisions to forgo electricity service altogether when the service fee is perceived to be too high for the value added to the household living conditions (Krumdieck & Hamm, 2009).

In the open flow control, fuel is used in response to loads. In contrast, in the feedback control system, activities, and therefore the loads created by them, are managed in order to meet the community value of uninterrupted supply. The standard feedback control model is used to model the energy system, including its customers (Krumdieck, 2013). The PDR feedback control system model illustrated in Figure 3.3 shows the remote electric energy system configuration for feedback control of activities when there is a known shortage of fuel. The forward elements of the system are the generator, distribution network and appliances. Unlike the open flow control model, the arrows between elements are actuating signals, not flows of energy. The real-time load that is input into the system highly depends on the three reference elements (explained in **section 3.5**) and the value community members put on the energy services they use from electricity. If the community places a high value on those services, then their response in actually changing their consumption behavior to ensure continued services for essential activities becomes the control-actuating signal.

The observation made by the primary feedback signal determines whether the power supply is available for normal operation or not. If the power system is not operating in its normal state, then behavior changes are required to deal with the situation. The system operator measures fuel supply and calculates if the real-time load pattern, $L(t)$, will exceed the supply. Then, a secondary signal will be delivered to the customers, prompting them to moderate their consumption to reduce the load pattern to MCD. If the fuel shortfall is becoming critical, a stronger feedback signal may be employed to prompt consumers to curtail non-essential activities and reduce the load pattern to SCD, until the fuel supply issue is resolved.

The implementation of the PDR program in a mini-grid consists of four main steps.

1. Characterize the end-use loads using energy audits, and then classify them further into three different levels of essentiality based on their value to the customer (refer to **section 2.4**).

2. Obtain the utility records and calculate hourly variation factors for the appliances along with the appliance saturation rate.

3. Generate the reference load curves and design the fuel consumption control strategy.

4. Finally, design the operator control system and test the system to 'teach' the utility operators.

4.2 End-use load characterization and classification

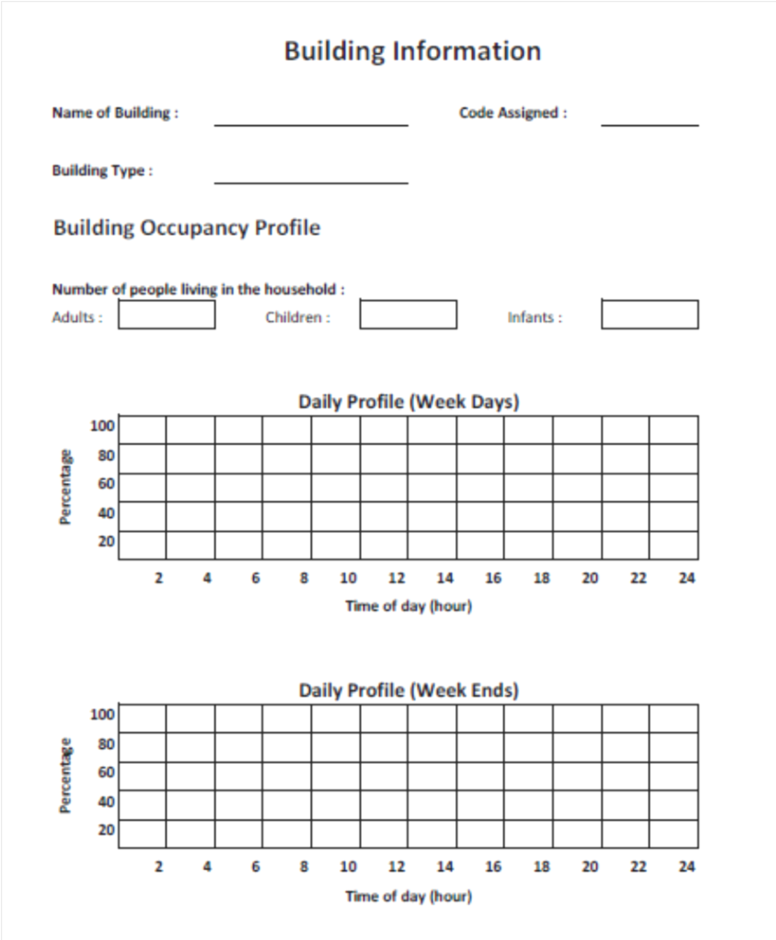
In small remote communities, a representative sample of homes is randomly selected for energy audits and end-use valuation surveys. As explained in **sections 2.7.1** and **2.7.2**, the energy audit is based on a Level-1 'walk-through' audit followed by a Level-2 'standard' audit. However, the standard methods need to be adapted for a village-scale energy audit. A new type of survey for the value characterization of the different end-uses was developed. This needs to be carried out for any community on the remote network, as particular activities and cultural aspects can be quite different for different locations (Mohamed, et al., 2010). The valuation survey and energy audit can focus on residential customers but the best PDR feedback control design would also include the commercial and governmental sectors.

4.2.1 Energy Audit

The energy audit designed for the PDR program consists of two parts: the *building occupancy profile* and the *electrical end-use appliance* audit.

Building Occupancy Profile

Building occupancy profile (BOP) is used to calculate the average hourly occupancy percentage of the household. The total occupants of the household are defined as the number of people living in that particular dwelling during the survey period. Anyone registered in the dwelling but not be present on the island for the period of the survey is not considered an occupant. Figure 4.1 shows the BOP audit sheet developed for the PDR program. In the audit sheet, every building is assigned a 'building code' by the auditor for administrative purposes. The building type is used to specify the number of floors the dwellings have above ground level.


Building Information

Name of Building : ____________ Code Assigned : ________

Building Type : ____________

Building Occupancy Profile

Number of people living in the household :
Adults : [ ] Children : [ ] Infants : [ ]

Figure 4.1: Audit sheet - Building occupancy profile

Information obtained by auditing the BOP is useful in finding the daily energy use profile of the particular household as well as the penetration level of the appliances.

Electrical end-use appliance audit

The electrical end-use appliance audit sheet is arranged in to different groups or areas that make up a normal household. This makes it easy to account for all appliances and it can be used to identify the most energy consuming area in the house. For example, all the appliances used in the bedroom are entered under the category 'Bedroom' on the sheet. Figures 4.2 and 4.3 show the electrical end-use appliance audit sheet developed for the PDR program.

Appliance / Area	Power (W)	Qty	Power Factor	Week Days Usage		Weekends Usage	
				Hrs/day	kWh/day	Hrs/day	kWh/day
Kitchen							
Florescent / Energy Saving Lights							
Incandescent Lights							
Fan							
Fridge/Freezer							
Blender/Mixer							
Microwave							
Toaster							
Rice Cooker							
Stove							
Kettle							
Sandwitch Maker							
Others							
Dining Area							
Florescent / Energy Saving Lights							
Incandescent Lights							
Fan							
Others							
Living Room							
Florescent / Energy Saving Lights							
Incandescent Lights							
Fan							
Air Conditioner							
Colour T/V							
VCR/DVD player							
Radio/Cassette							
Computer							
Monitor							
Printer							

Figure 4.2: Electrical end-use appliance audit sheet (Part 1)

Appliance / Area	Power (W)	Qty	Power Factor	Week Days Usage		Weekends Usage	
				Hrs/day	kWh/day	Hrs/day	kWh/day
Living Room (Continued...)							
Sewing Machine							
Others							
Bedrooms							
Florescent / Energy Saving Lights							
Incandescent Lights							
Fan							
Air Conditioner							
Others							
Toilets							
Florescent / Energy Saving Lights							
Incandescent Lights							
Hair Dryer							
Shaver							
Others							
Laundary							
Florescent / Energy Saving Lights							
Incandescent Lights							
Washing Machine							
Iron							
Clothes Dryer							
Others							
Misc							
Water Pump							
Electric Insect Repellent							

Figure 4.3: Electrical end-use appliance audit sheet (Part 2)

The information required on the audit sheet includes the number of a particular appliance, its power rating, and an estimated value for the number of hours each appliance is utilized. The information obtained from this sheet along with the BOP can be used to estimate an average value for the electrical energy usage pattern for the particular household. The information can also be used for designing awareness activities for consumers who wish to improve the efficient utilization of electrical energy.

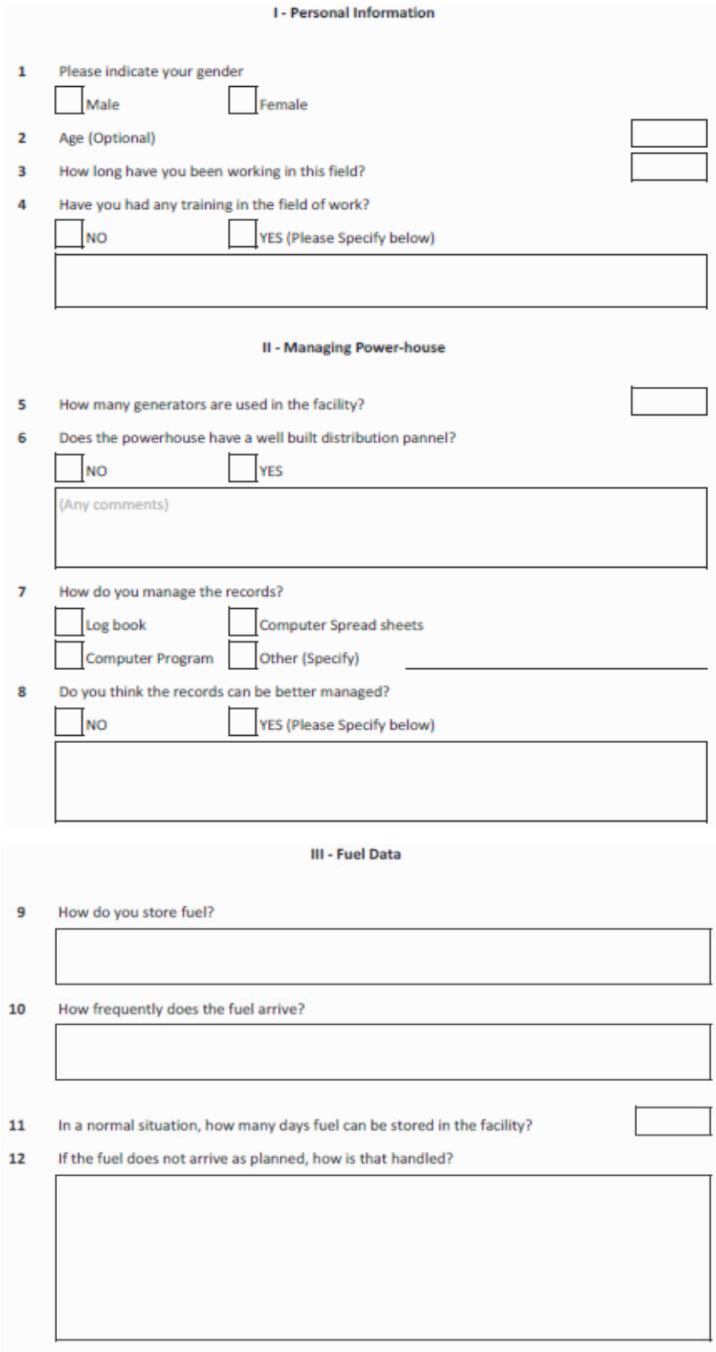
4.2.2 Valuation or adaptability survey

The valuation or adaptability survey is conducted using the questionnaire shown in Appendix A4. The questionnaire is designed such that all the household end-use appliances can be categorized into the three categories of essentiality ('deferrable', 'optional' and 'essential') discussed in **section 2.4**.

The survey also helps in finding out the current situation of the island based on the three 'reference elements'. It identifies key elements such as the consumers' views on the status of the power generation system, how much information they have on the operation, the impact on the environment, etc. The questionnaire is organized into nine main categories. The first four categories focus on obtaining general knowledge about the building and the amount of energy that is being consumed. Categories five to seven are about the concerns the residents have on the price of energy, energy security and the environment. The eighth category consists of questions regarding how the residents of the households will react to a PDR signal passed on due to a constraint in power generation. This category is most essential in obtaining the three VPP reference levels required for the PDR program. The last category regards the level of knowledge the consumers have about the power supplier and the difficulties faced during power generation. This category also asks for the customers' opinions on the most efficient method for communication if a PDR signal has to be generated.

4.2.3 Survey of the powerhouse operators

Apart from the energy audit and the adaptability survey, two more survey questionnaires were prepared for the powerhouse operators. The aim of the first questionnaire, shown in Figure 4.4, is to understand the powerhouse operators' educational standards and field experiences, as well as the environment they work in. This questionnaire is handed over to them before they are introduced to the graphical user interface (GUI). The second questionnaire shown in Figure 4.5 is for the operators to complete after they have been introduced to the GUI. This questionnaire will help in understanding the opinion of the powerhouse operators regarding a GUI for managing the powerhouse operation better. It will also determine if the operators feel that such a program can help them to organize and manage energy constraint situations better.



I - Personal Information

1 Please indicate your gender

☐ Male ☐ Female

2 Age (Optional) ☐

3 How long have you been working in this field? ☐

4 Have you had any training in the field of work?

☐ NO ☐ YES (Please Specify below)

II - Managing Power-house

5 How many generators are used in the facility? ☐

6 Does the powerhouse have a well built distribution pannel?

☐ NO ☐ YES

(Any comments)

7 How do you manage the records?

☐ Log book ☐ Computer Spread sheets

☐ Computer Program ☐ Other (Specify)

8 Do you think the records can be better managed?

☐ NO ☐ YES (Please Specify below)

III - Fuel Data

9 How do you store fuel?

10 How frequently does the fuel arrive?

11 In a normal situation, how many days fuel can be stored in the facility? ☐

12 If the fuel does not arrive as planned, how is that handled?

Figure 4.4: Powerhouse operator questionnaire 1

1 How well did you understand the computer program?

Not at all				Very well
1	2	3	4	5

2 Do you think such a computer program can assist you in managing the records better?

☐ YES ☐ NO

(Any Comments)

3 Do you think if there was any fuel constraint situation, such a program can help you in managing the situation better?

☐ YES ☐ NO

(Any Comments)

4 What other features will you recommend to be incorporated in the program?

5 Will you recommend such a computer program to be used in your work place?

☐ YES ☐ NO

Figure 4.5: Powerhouse operator questionnaire 2

4.3 Obtain utility records

The second step of implementing the PDR control system is to obtain the past and present records from the utility provider. Information required includes hourly load data, fuel consumption along with fuel delivery and storage details, and available generators and their specifications. Specifications of the generation plant and fuel supply must be acquired from the utility and verified by a site visit as it is not unusual for remote powerhouses to have different configurations to those indicated by central records. Historical load and fuel use data must also be gathered and correlated with any known historical end-use trends. In many remote communities, these kinds of records are not automatically logged by computer and may need to be extracted and analyzed from written logs and discussion with the local operators. Historical trends may include population migrations and the introduction and uptake of new appliances.

Appliance saturation rate and hourly variation factors for the appliance categories are also required for implementation of the PDR program. The appliance saturation rate and hourly variation factor is defined in **section 2.8.3**. Appliance saturation rate is calculated by

$$s_i = \frac{n_i}{N} \times 100 \qquad \textbf{Eq. 8}$$

where, s_i is the saturation rate of the appliance category i, n_i is the number of households with at least one appliance belonging to category i and N is the total number of households in the energy audit. The appliance saturation rates are calculated from the energy audit data.

The hourly variation factors (HVF) for different household items have to be estimated by using the energy audit and survey data. Literature has shown that HVF are human behavior related factors. There is no available HVF for appliances that can be used on remote communities.

4.4 Reference load curves and fuel consumption control

The reference load curves are the hourly load patterns of the entire community and are generated using the concept of maximum diversified demand (MDD). These load curves represent the estimated hourly value that is expected at different levels of VPP. These load patterns will be used by the powerhouse operators to calculate the level of VPP that needs to be asked of consumers during a constraint situation.

4.4.1 Reference load curves

Normal Demand (ND)

The reference load curve for normal demand (ND) is modelled according to the energy audit data, applying the diversified demand concept, and then fitting the model to historical data. The equation for calculating the load curve for ND can be obtained by using **Eq.4** to **Eq.7**, and is expressed as

$$ND(t) = \sum_{i=1}^{p} [ADD_i \times C \times s_i \times F_i(t)] \qquad \textbf{Eq. 9}$$

where $ND(t)$ is the value of normal demand at time t, and $F_i(t)$ is the HVF of the appliance category i during normal operation at the given time.

Moderately Constrained Demand (MCD)

During the survey and energy audit, customers nominate optional end-uses they could easily defer, reduce or curtail without great impact. Therefore, the hourly variation factor in the MCD condition differs from the normal condition, for some of the appliance categories. The reference load curve for an MCD condition is calculated using the equation

$$MCD(t) = \sum_{i=1}^{p}[ADD_i \times C \times s_i \times F_i(t) \times F_{mi}(t)] \qquad \textbf{Eq. 10}$$

where *MCD(t)* is the value of medium constrained demand at time *t*, and F_{mi} is the percentage reduction in HVF of the appliance category *i* during an MCD condition at the given time.

Severely Constrained Demand (SCD)

The load curve for the SCD is the hourly load pattern obtained when consumers curtail the use of all except essential appliances. Therefore, this situation should only be generated when load curtailment is unavoidable. To minimize the longevity of this situation, the utility operator can introduce intermittent periods of severe constraint signals for one or two hours at peak demand times. The operator can have a text message list for households with high loads such as air conditioners, and if there is a possibility of an SCD, messages can be sent beforehand to those households to "please curtail the use of air conditioners for two hours if at all possible". The reference load for the SCD condition is calculated using the equation

$$SCD(t) = \sum_{i=1}^{p}[ADD_i \times C \times s_i \times F_i(t) \times F_{ei}(t)] \qquad \textbf{Eq. 11}$$

where *SCD(t)* is the value of severely constrained demand at time *t*, and F_{ei} is the percentage reduction in HVF of the appliance category *i* during an SCD condition at the given time.

4.4.2 Real-time monitoring and fuel consumption control

Management of fuel consumption is one of the most important aspects of the PDR program. Apart from emergency situations such as the break-down of a generator where a DR is required to manage the load, the PDR program utilizes the rate of fuel consumption to generate the DR signals.

First, the maximum allowable consumption rate ($\emptyset_{max}$) is calculated. This is the maximum rate at which fuel can be consumed such that the available fuel in stock does not run out before the next shipment date. This can be calculated using the equation

$$\emptyset_{max} = \frac{Q}{T} \text{ litres/day} \qquad \textbf{Eq. 12}$$

where $\emptyset_{max}$ is the maximum allowable fuel consumption rate, Q is the amount of fuel available in stock (litres) and T is the time until next stock arrival (days).

To maintain a sustainable fuel consumption, if the real-time fuel consumption rate (RFC) reaches $\emptyset_{max}$, a DR signal has to be generated to let consumers know the level of constraint required. However, to withdraw the constraint level and resume ND consumption, a second signal has to be generated. This signal is generated if a new fuel shipment arrives or if the RFC reaches a minimum tolerance level ($\emptyset_{min}$). This can be set such that there is a reserve of one day's fuel. If, from the historical data log of the island power house, the average amount of fuel consumed per day is δ, then

$$\emptyset_{min} = \emptyset_{max} - \delta \qquad \textbf{Eq. 13}$$

To simplify for the power house operators, the PDR program developed can make use of the accumulative values of the fuel consumption rates. This way, it will be easier to track how much fuel has been consumed at any given time. Figure 4.6 shows how the RFC can be controlled within the tolerance limits. R_{max} is the accumulative $\emptyset_{max}$ and is calculated using the equation

$$R_{max}(t) = \sum_{t=1}^{t} \emptyset_{max}(t) \qquad \textbf{Eq. 14}$$

and R_{min} is the accumulative $\emptyset_{min}$ and is calculated using the equation

$$R_{min}(t) = \sum_{t=1}^{t} \emptyset_{min}(t) \qquad \textbf{Eq. 15}$$

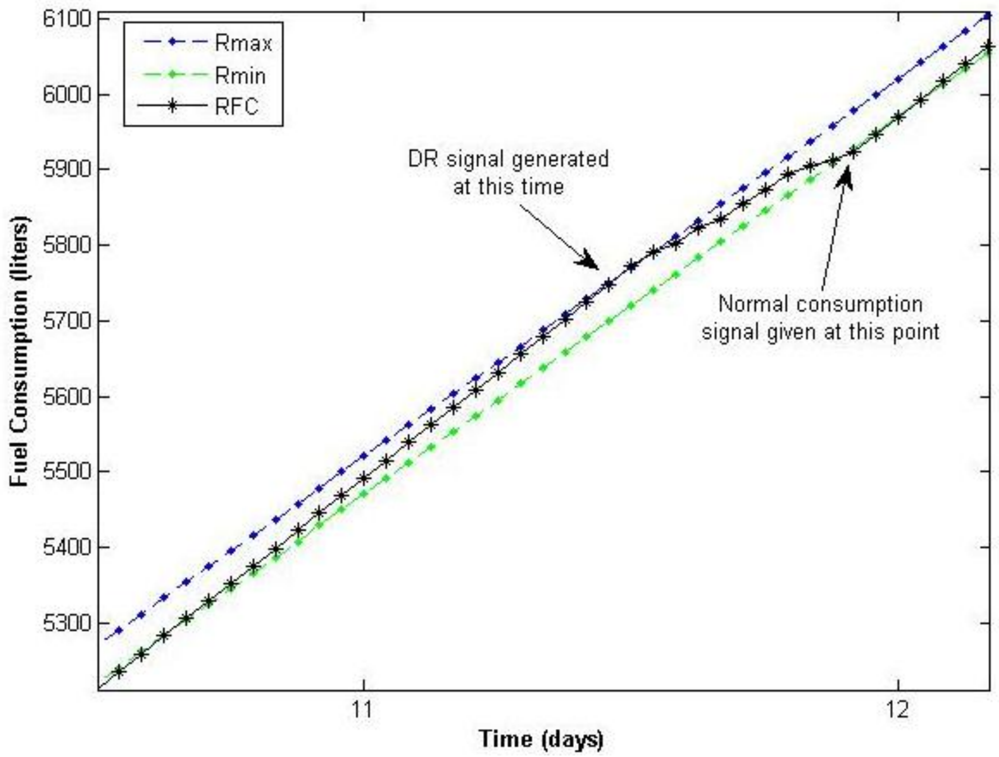


Figure 4.6: Control of fuel consumption rate within tolerance limits

The control system design has been discussed in terms of fuel shortage events, which have become common occurrences for remote communities since the second Gulf War, which caused sharp fuel price increases (J. L. Smith, 2009). Over the past five years, demand growth in remote communities has also become a fuel supply issue. The number and types of appliances available to customers may grow the load capacity to be greater than the capacity of the powerhouse or fuel storage facility or even the fuel supply vessel. In tropical areas, proliferation of air conditioners has greatly increased the power demand to the point where normal fuel supplies can be consumed prior to the next scheduled shipment. This trend can accelerate in the future, but the design for the feedback control presented in this thesis can be used for over-consumption as well as for fuel shortage.

4.5 Design of utility operator control system to generate feedback signal

Literature shows that powerhouses in remote communities are not equipped with sophisticated control systems that can log hourly data automatically (Worrall, 2006). Utility operators have to log data manually either in specially assigned log books or on a spread sheet created in a computer. In this thesis, the author designed a simple computer based operator control system named *Utility-Fuel-Constraint Operator Control System* (UFCOCS), which can be used in the powerhouse. This control system monitors load levels and fuel consumption, and suggests a possible PDR level requirement. It can also predict hourly load and fuel consumption such that the operator can anticipate a system constraint before it happens. Figure 4.7 is a general illustration of the main PDR design showing the location of UFCOCS. The UFCOCS is added to the system as an interaction to the general feedback element, and assists in generating the required PDR signal. Figure 4.8 illustrates the control diagram of the UFCOCS, including its four main sub-systems.

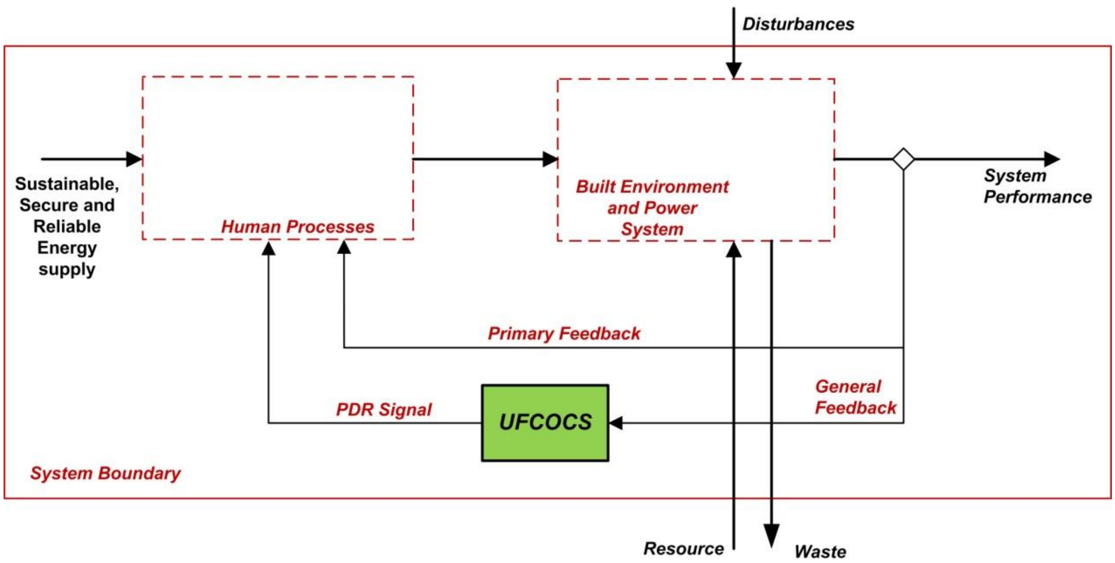


Figure 4.7: General illustration of the PDR design showing the location of UFCOCS

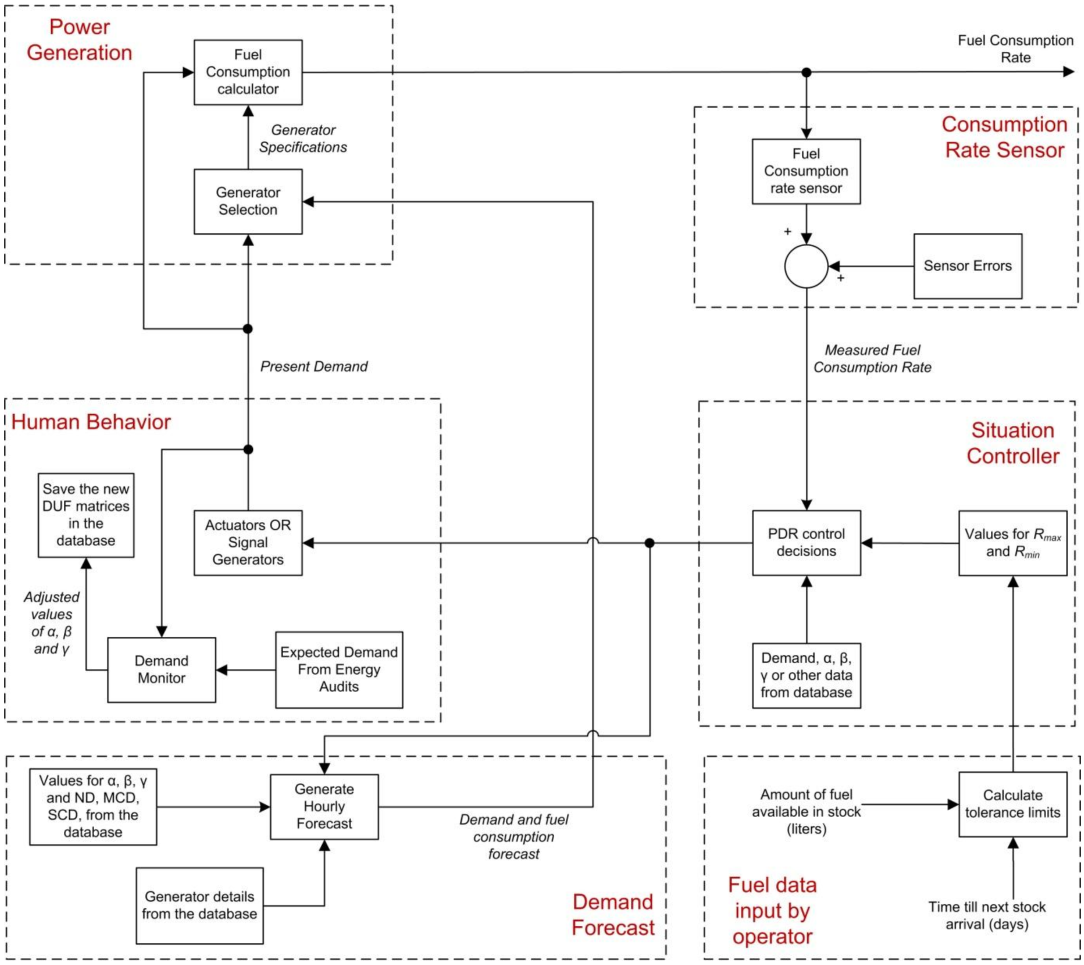


Figure 4.8: Utility-Fuel-Constraint Operator Control System (UFCOCS) model

4.5.1 Consumption rate sensor and situation controller sub-system

In more developed power generation systems, the generator fuel consumption rate can be automatically monitored, but in remote area power generation systems, the fuel rate is monitored from the generator panel board[1]. If the fuel rate is not displayed in the generator panel board, then it has to be estimated using the technical specification sheet provided with the generator[2]. Appendix A5 shows the table for approximate fuel consumption rates of different generator ratings (DieselService&Supply, 2013). The real-time fuel consumption rate is used by the situation controller along with the pre-set fuel consumption tolerance limits, R_{max} and R_{min}, and different other behavior

[1] Generators that comes with a digital panel board, normally include the function of displaying the fuel consumption rate.
[2] Every generator comes with its specification sheet, which provides the details including the generator's approximate fuel consumption rates. If the remote community does not have the information sheet, the chart presented in Appendix A5 of this thesis can be used as a guideline.

related factors read from the database to make the PDR control decisions. The tolerance limits are calculated by the program using **Eq. 12** to **Eq. 15**, when the operator enters the values for *Q* and *T*. The PDR controller decisions are output into both *demand forecast* and *human behaviour* sub-systems.

4.5.2 Demand forecast sub-system

The PDR decisions from the situation controller are fed into the 'hourly forecast' generating function in the demand forecast sub-system. To forecast the hourly load and the respective fuel consumption, this study has introduced a novel concept that utilizes a matrix variable called the *demand-use-factor* (DUF) matrix.

Demand-use-factor (DUF) matrix

The fraction of demand being used by a specific household or a group of households at a specific time with respect to the VPP is called the *demand-use-factor* (DUF) for that particular time. The DUF matrices used by this research are α, β and γ, and are calculated using the equations:

$$\alpha_{(v,m,d,h)} = \frac{L(t)-MDC(t)}{\Delta N(t)} \qquad \textbf{Eq. 16}$$

$$\beta_{(v,m,d,h)} = \frac{L(t)-SDC(t)}{\Delta M(t)} \qquad \textbf{Eq. 17}$$

$$\gamma_{(v,m,d,h)} = \frac{L(t)}{\Delta S(t)} \qquad \textbf{Eq. 18}$$

where, *L(t)* is the real-time load at time *t*; *MCD(t)* and *SCD(t)* are the values of MCD and SCD at time *t*; and *v*, *m*, *d* and *h* are the governing conditions for the DUF value. $\Delta N(t)$, $\Delta M(t)$, and $\Delta S(t)$ are defined as:

$$\Delta N(t) = ND(t) - MCD(t) \qquad \textbf{Eq. 19}$$

$$\Delta M(t) = MCD(t) - SCD(t) \qquad \textbf{Eq. 20}$$

$$\Delta S(t) = SCD(t) \qquad \textbf{Eq. 21}$$

Governing conditions for DUF matrix

The demand-use-factors depend on four basic conditions. These conditions are:

- Level of VPP (*v*) - The DUF matrix value depends on the level of constraint being practiced at the time in focus. As explained in **section 3.4**, this factor has three levels; normal, medium or severe. These levels are represented by 1, 2 and 3, respectively. Hence, if the level of VPP is normal, then $v = 1$.

- Month of the year (*m*) - The second condition for the DUF matrix is to represent the season. The energy pattern differs depending on the season. The consumption pattern for winter is different from the consumption pattern for summer. In a country such as New Zealand, there are 4 levels that represent '*m*': summer (*m=1*), autumn (*m=2*), winter (*m=3*) and spring (*m=4*). However, for an equatorial country such as the Maldives, there are only two levels, namely, North-east monsoon (*m=1*) and South-west monsoon (*m=2*).

- Day of the week (*d*) - The energy consumption pattern for a particular community has been observed to vary depending on the day of the week (Muto, 1996). These patterns can be further categorized into weekdays (*d*=1) and weekends (*d=2*). Even though public holidays have not been mentioned, they are included in the weekend pattern. Hence, the day of the week is divided into two levels.

- Hour of the day (*h*) - The last governing condition for the DUF matrix value is the hour of the day. The electrical energy consumption varies dramatically depending on this. Therefore, '*h*' is sub-divided in to 24 levels.

Each DUF matrix has a total of 576 factors (3levels x 4months x 2days x 24hours). The initial values for the DUF matrices are assumed to be '1'. This means that the program assumes that the people will consume energy as per the reference load pattern that has been obtained using **Eq. 9** to **Eq. 11**. Once the program is run, these values change based on the real-time load pattern.

Hourly forecast generation

The hourly forecast generation function receives the output from the situation controller, the values of α, β and γ, and the results of the energy audit from the database, as input data. The function then processes this data to obtain the demand and fuel consumption forecast. Figure 4.9 shows the three stages of hourly forecast generation function.

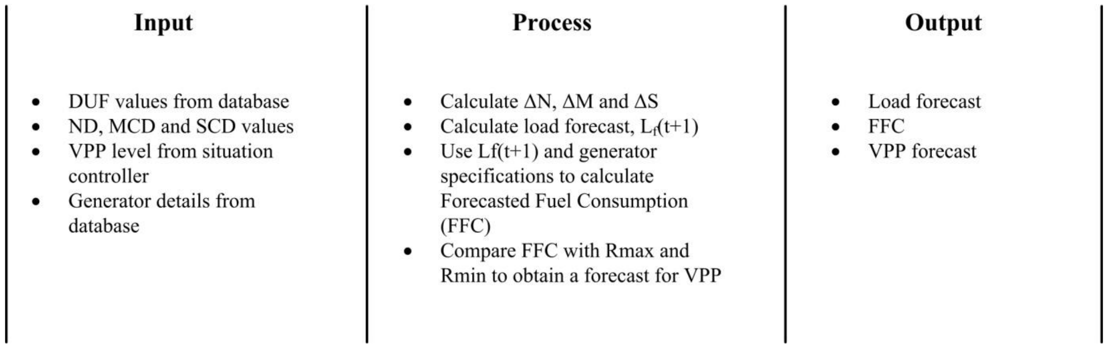


Figure 4.9: Three stages of the hourly forecast generation function

In the processing stage, $\Delta N(t+1)$, $\Delta M(t+1)$, and $\Delta S(t+1)$ are calculated using **Eq. 19** to **Eq. 21**, respectively. However, in the equations, the time *t*, is replaced by '*t*+1', to calculate the values for the next hour. The equation to calculate the load forecast is:

$$L_f(t+1) = \alpha_{(t+1)}.\Delta N(t+1) + \beta_{(t+1)}.\Delta M(t+1) + \gamma_{(t+1)}.\Delta S(t+1) \qquad \textbf{Eq. 22}$$

where L_f is the forecasted load and *(t+1)* represents the value for the next hour.

To estimate the forecasted fuel consumption (FFC), the calculated L_f is compared with the generators' fuel consumption specifications to determine a value.

For example, if the calculated value of L_f is 72kW and the generator's specifications are:

Rated capacity = 160kW

Fuel consumption rates:

1/4 Load = 13.5 L/hr	*1/2 Load = 23.3 L/hr*
3/4 Load = 34 L/hr	*Full Load = 45.4 L/hr*

then the value of *FFC = 23.3 L/hr*.

In the example above, the forecasted load is 72kW, which is approximately half the rated capacity of the generator in operation. Therefore, the approximate fuel consumption of the generator will be its half-load consumption rate, which in this case is 23.3L/hr.

The fuel consumption and demand forecast output from this subsystem is fed into the generator selection process.

4.5.3 Human behavior monitoring sub-system

The PDR decisions from the situation controller are also fed into the 'actuators or signal generators' of the human behavior monitoring sub-system. The signal generator's function is to inform the people about the level of VPP that is being practiced. If the situation controller has sent a control signal suggesting a MCD situation, the signal generator will inform the consumers about the same. In a remote energy system, this signal can be a written notice in a community centre, an announcement in a religious centre, or if possible, it can be a text message sent to the participating customers' mobile phones.

The resulting demand is fed into the *demand monitor* of this sub-system. The demand monitor will compare the real-time load with the reference load pattern and compute the adjusted values for the DUF matrices.

For example;

For a Monday *(d = 1)* in December *(m = 4),* at 2pm *(h = 14),* when the VPP level is at normal *(v = 1),* if the DUF value is calculated to be 0.8, then the adjusted DUF values will be:

$$\alpha_{(1,4,1,14)} = \frac{[previous\ value\ of\ \alpha_{(1,4,4,14)}\ from\ database]+0.8}{2}$$

$$\beta_{(1,4,1,14)} = 1$$

$$\gamma_{(1,4,1,14)} = 1$$

The community demand, observed due to the human behavior, is fed into the *power generation* subsystem.

4.5.4 Power generation sub-system

This is the sub-system that represents the working of the generator and its operator. The details of present demand from the human behavior sub-system are input into the 'generator selection' and 'fuel consumption calculator' functions of this sub-system. The purpose of the generator selection function is to evaluate if, depending on the forecasted load and the present load, the generator on load needs to be switched, and the load need to be transferred to the next available generator. This process will be performed by the operator. The operator control system displays the results of the demand forecast and the present load. The operator will decide to switch the generator depending on these values and the capacity of the currently operation generator. Once the decision is made, the operator chooses the generator in operation and the new value of fuel consumption rate is generated. This will complete the closed loop system shown in Figure 4.8.

4.6 Graphic user interface of UFCOCS

The UFCOCS designed in this thesis was developed as a graphical user interface (GUI) to be used by the utility operator, using Microsoft Visual Basic[3]. Figure 4.10 illustrates the input data required from the operator.

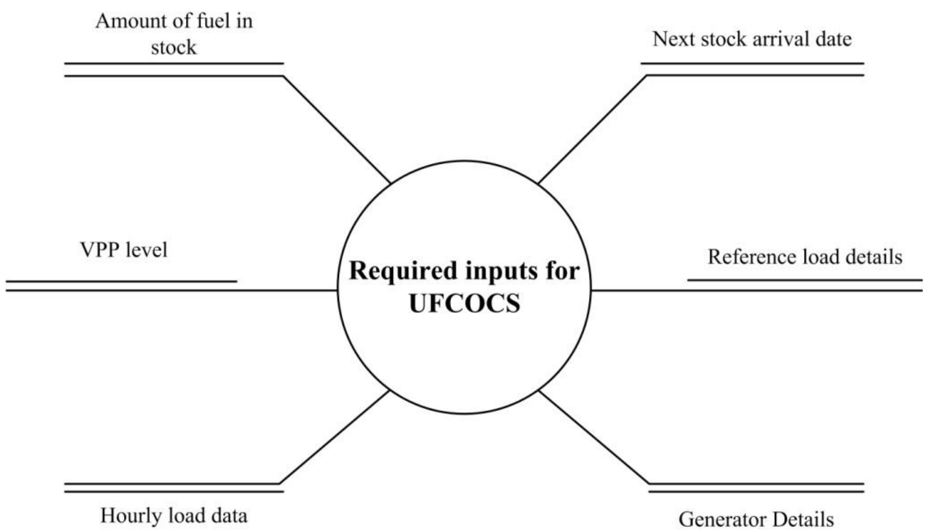


Figure 4.10: Input data required for UFCOCS from the operator

[3] Visual basic is a third-generation event-driven programming language and integrated development environment (IDE) from Microsoft. Visual basic was first released in 1991 and it can be used to create both simple and complex GUI applications. For more information go to "http://msdn.microsoft.com/en-us/vstudio/ms788229.aspx"

The operator will have to enter the amount of fuel being received (Q) and the next stock arrival date (T), every time a new stock of fuel arrives. The specifications of all the generators available in an operating condition also need to be entered during the initial start-up of the system. Whenever there is a change in available generators, this change has to be updated in the program. The UFCOCS also requires details of the reference load patterns that have been obtained from the energy audit and surveys. The system operator needs to keep entering the hourly load data, at the same time selecting the generator in operation as well as the VPP level.

Once this data is entered into the UFCOCS, the program processes the information in order to obtain the required outputs and data to be stored. The processes and calculations performed by the program are illustrated in Figure 4.11.

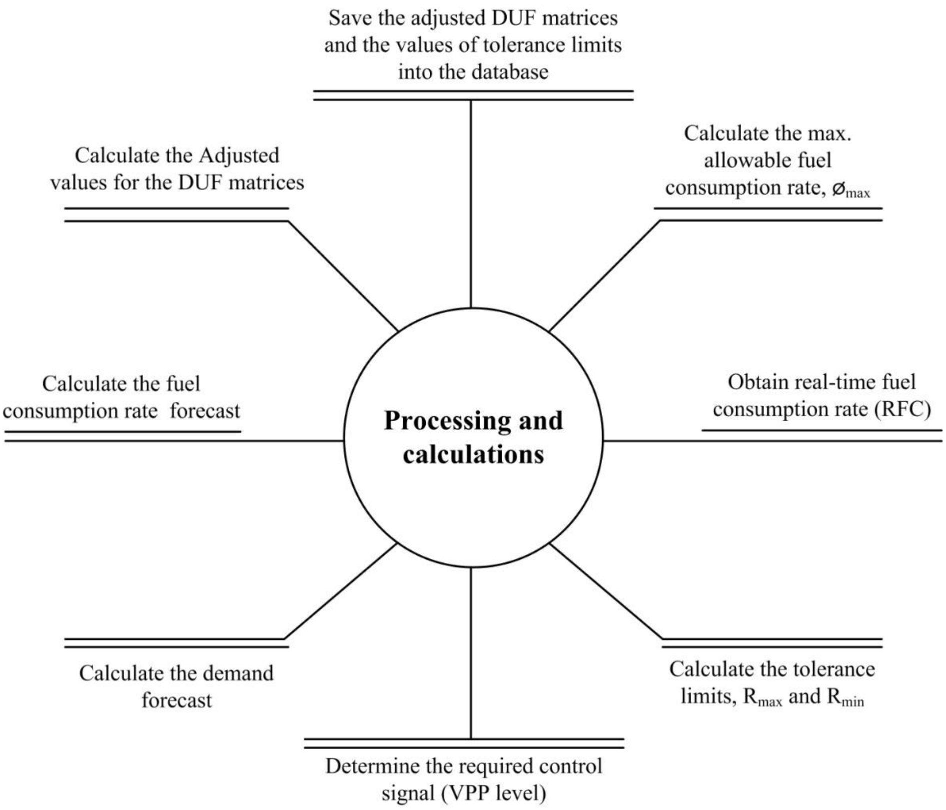


Figure 4.11: Calculations and processing performed by UFCOCS

Every time a new value for Q and T is entered into the system, the program will calculate the new values for $\emptyset_{max}$ as well as R_{max} and R_{min}. These values are then saved to the database. From the input screen, when the operator selects the generator in operation, the program reads the generator's specifications from the database and uses this data to calculate fuel consumption rates. In UFCOCS, the operator does not have to enter the real-time fuel consumption rate, *RFC*. The value of *RFC* is calculated by the program hourly, when the system operator enters the real-time load on the generation system. After comparing the value of RFC with the tolerance limits, the program will generate the required VPP level for the present situation. The program also calculates the demand and fuel consumption rate forecast for the next hour, using the DUF matrices stored in the program database. At the same time, the program calculates the adjusted values for the DUF matrices whenever the operator enters new hourly load data. These adjusted values of the DUF matrices are then stored back into the database.

The calculations are then output to the GUI of the UFCOCS. The output data generated by the program is illustrated in Figure 4.12.

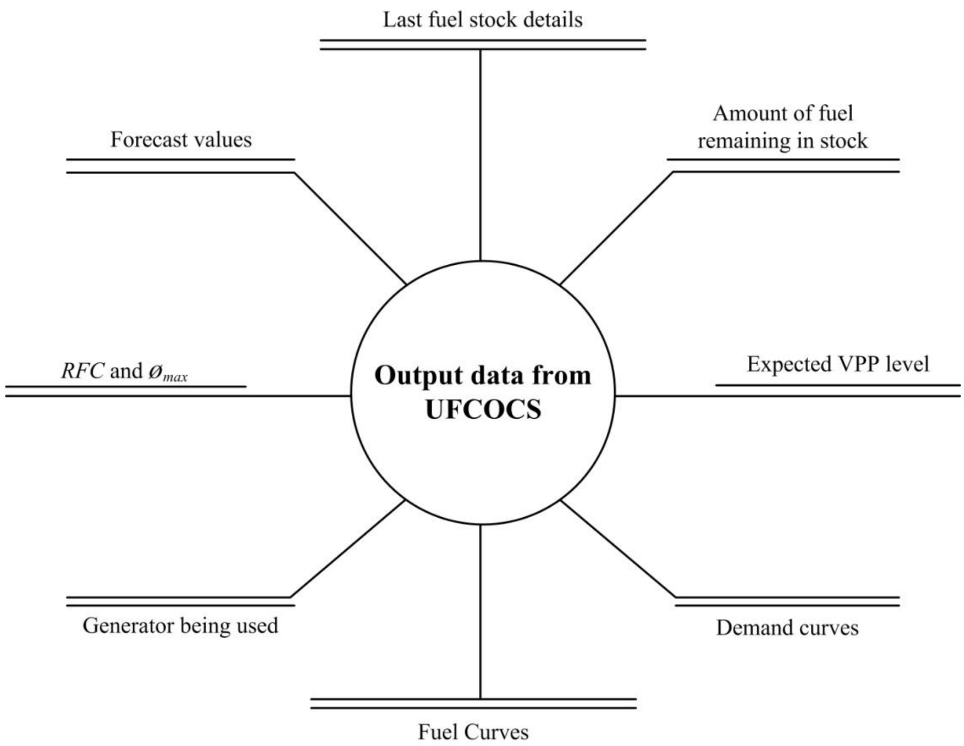


Figure 4.12: Output data from the UFCOCS

The demand and fuel curves that are generated are projected onto a graph that is updated on an hourly basis when the operator enters new values. This demand graph shows the real-time load along with the three reference demand curves so that the operator has a better understanding of the present situation of the energy system. The fuel graph illustrates the *RFC* along with the tolerance limits. This helps the operator to finalize a VPP level when it is most required for the PDR system. Figure 4.13 is a screen shot of the main front page of UFCOCS user interface.

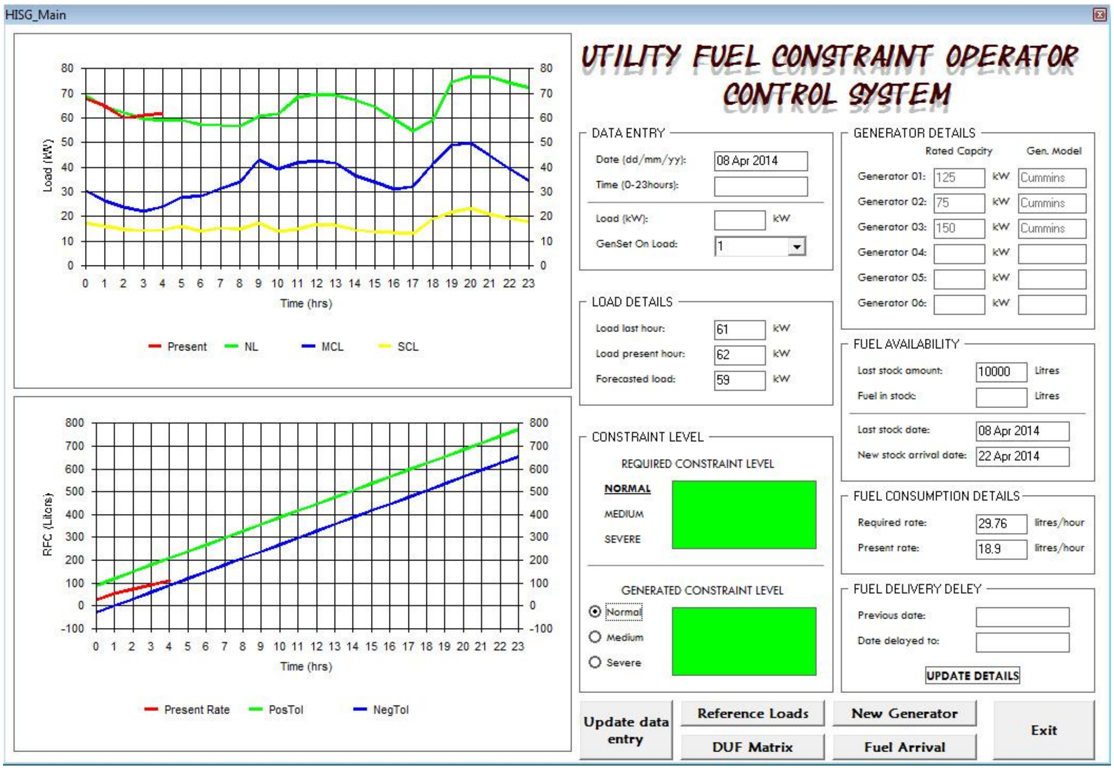


Figure 4.13: Screen shot of the UFCOCS interface front page

Appendix A7 provides all of the screenshots and the full Visual Basic code for the GUI developed for the case study carried out for this thesis. The UFCOCS is a GUI that was written specifically for this case study, therefore, further adjustments may need to be carried out when trying to implement this GUI elsewhere.

4.6 Summary

The PDR implementation procedure for a remote mini-grid and the GUI developed by the author was discussed in this chapter. The first step of the implementation procedure is the characterization of the end-use loads based on their importance to the customer. To perform this step, an energy audit and an energy survey, adapted from standard methods to fit a village scale, must be carried out. The audit and survey tools designed for this thesis to fit a village scale were presented in this chapter.

The next step of implementation is to gather the utility records and calculate the HVF and the appliance saturation rate. Utility records include both past and present data available on hourly load, information on the available generators including their fuel consumption, and fuel delivery and storage details.

The third step is to design the fuel consumption control strategy and build the reference load curves. The graph showing the reference load curves depends on the results of the energy audit and survey data. The concept of the use of MDD in this study to generate the reference load curves for the three levels of VPP was explained. How the RFC can be controlled within a tolerance limit in order to manage the amount of fuel available was also explained.

The fourth step of the implementation procedure was the design of the operator control system. A simple computer based operator control system named *Utility-Fuel-Constraint Operator Control System* (UFCOCS) was developed for use in the power house. The UFCOCS has four main sub-systems: *consumption rate sensor and situation controller*, *demand forecast*, *human behavior monitoring*, *and power generation*.

The graphical user interface (GUI) designed for the UFCOCS was also discussed and illustrated in this chapter.

So far, the literature on remote power supply systems and their control strategies has been reviewed, a novel methodology for demand management in remote communities, PDR, has been presented and its implementation procedure for introduction into a mini-grid was explained. The next chapter discusses, the concept validation for PDR using a case study carried out on an island community in the Maldives.

CHAPTER 5

CONCEPT VALIDATION

"We cannot solve our problems with the same thinking we used when we created them"

-Albert Einstein-

THE design of a novel real-time feedback control system for a resource constrained power grid that utilized participatory demand response from end-users was designed and presented in the previous chapters. This chapter describes the case study that was conducted by the author in order to validate the concept of the proposed system. The concept validation assessments were carried out in an island in the Maldives. In sections 5.1, an introduction to the case study island is presented. The study has two main concepts to be validated and these concepts are explained in section 5.2. The concept validation study that was carried out on the island is discussed in section 5.3, which explains how the PDR signalling was carried out and what messages were sent to the participants. Finally, the chapter concludes with a summary in section 5.4.

5.1 Case study island

The concept validation trials were carried out on Fenfushi, an island located at the extreme Southwest end of South Ari Atoll, of the Republic of Maldives. The island is approximately a hundred kilometers from Male', the capital island of Maldives. The Republic of Maldives is an island nation in the Indian Ocean formed by a double chain of 26 natural atolls. The atolls consist of large ring shaped coral reefs supporting numerous small islands. The islands have a warm and humid tropical climate, which is described as monsoonal. The Southwest monsoon, or the wet season, lasts from May to July, while the transition period from the Southwest monsoon to the Northeast monsoon lasts from August to October. The Northeast monsoon is the dry season, lasting from November to January. Then the transition period back to the Southwest monsoon lasts from February to April.

When the case study was carried out, there were a total of 120 residential households on Fenfushi, with an island population of 831. The government sector facilities included a health centre, an island office with the judiciary, and a school. There were two mosques and a pharmacy, which operated as public institutions. Commercial institutions included eight grocery shops and two cafés. The industrial sector included three carpentries and two boat yards where boats were under construction and refurbishment.

5.1.1 Electrical power generation

The island had a powerhouse, which is now operated by the government. It was community owned until recently, when the government took over power generation for the island in February 2012. The power house operates 24 hours a day, supplying electricity for the entire island. The generation system consisted of four diesel generators (see Figure 5.1), 3 of which are operational. The fourth generator is currently not being used since it is under-rated compared to the community load. Two of the generators, namely *'Gen Set 1'* and *'Gen Set 3'*, were in operation at the start of the field survey. During the survey period a third one, *'Gen Set 2'*, was commissioned and brought into operation, while *'Gen Set 4'*, is not being utilized. Table 5.1 summarizes the available generators in Fenfushi's powerhouse.

Figure 5.1: Generator arrangement in Fenfushi powerhouse

Table 5.1: Summary of available generators

Generator	**Capacity (kW)**	**Generator Type**
Gen Set 1	128	Cummins
Gen Set 2	160	Cummins
Gen Set 3	80	Cummins
Gen Set 4	40	Cummins

5.1.2 Fuel supply and storage

A fuel barge supplied diesel fuel to the island every 20 days. Having the powerhouse located near the island's main habour made the transfer of diesel easy. The diesel fuel was pumped into the main fuel tanks of the powerhouse using a long, flexible pipe. A panoramic view of how the fuel was pumped into the powerhouse is shown in Figure 5.2.

Figure 5.2: Diesel fuel delivery and transfer

The fuel storage system consisted of two main fuel storage tanks located just outside, shown in Figure 5.3, and a day tank located inside the powerhouse building, shown in Figure 5.4. The fuel from the main tanks was transferred to the day tank regularly for, use by the generators. The fuel in the day tank was monitored and logged daily by the powerhouse operators.

Figure 5.3: Main fuel storage tanks located outside the powerhouse building

Figure 5.4: Smaller day tank located inside the powerhouse building

5.1.3 Power transmission and distribution

The powerhouse had a well-built distribution control panel located inside an air-conditioned room in the same building. The control panel was equipped with all the required metering devices but did not have synchronizing ability, so the generators were switched manually. According to powerhouse staff, the generators were switched twice daily, first at 2:30 a.m. and again at 10:30 a.m. Gen Set 3, with the lowest capacity rating (80kW), ran from 2:30 a.m. till 10:30 a.m., then during the next shift Gen Set 1 (128kW) operated. This had been the case up until the generator with the highest capacity rating, Gen Set 2 at 160kW, was commissioned.

Figure 5.5: Distribution control panel

There were three feeder cables running from the distribution panel into the island. These feeder cables were 35mm^2,three-wire armoured underground cables running along the length of the island as shown in Figure 5.6. Distribution boxes were located at several locations along the route of the feeder cable. These distribution boxes were used to connect the individual households to the electric grid.

Figure 5.6: Distribution feeder cable layout (image taken from Google Earth)

5.1.4 Powerhouse operation and tariff structure

During the survey period, the powerhouse was staffed with a total of six employees, working in three shifts of two employees each. The powerhouse had one desktop computer for administrative use, but the data logging was done manually on printed sheets as shown in Appendix A3. Readings were taken hourly, and consisted of the following measurements:

- generator number
- time
- total supply voltage in volts (V)
- frequency in Hertz (Hz)
- total current in amperes (A) on each phase; Red, Yellow and Blue
- total load in kilo watts (kW) and kilo-volt-ampere (kVA)
- total generated units for the generator in kilo-watt-hours (kWh)
- power factor (PF)
- oil Pressure in (bar)
- water temperature in degrees Celcius (^{o}C)
- battery voltage in volts (V)

Every month staff walked to each individual household and noted the house-meter readings to calculate the amount of energy used in kWh. When the powerhouse operated as a community owned institution, the tariff used to be a flat rate of approximately US$0.4 per unit (kWh). Once the powerhouse started its operation as a government institution, the tariff structure changed such that the rate per unit became based on different bands of usage. The present tariff structure is shown in Table 5.2.

Table 5.2: Fenfushi island tariff structure

Band (30 days)	Rate (US$)	
	Domestic	Commercial, Government and Institutes
First 100 units	0.14	0.29
Units 101 to 200	0.18	0.37
Units 201 to 300	0.23	0.42
Units 301 and above	0.23	0.49

5.2 Key concepts for validation

The literature in **section 2.3** showed that energy consumers in the residential sector tend to manage their end-use consumption if they are equipped with technology that updates them. However, the motivation embedded in the technologies has mostly been fiscal benefits, environmental impact or at times security of the power system. The PDR program approaches energy consumers with the offer to participate willingly in a cooperative effort to manage the energy utilization. It requires community involvement in a cohesive environment, sharing knowledge, observing the difference and learning through participation. As a consequence, the key concepts that require validation are the PDR control system design, and the operator control system. In other words, validation on a methodology that answers the question: "*how can we activate the PDR response to achieve the targeted load adjustments?*" The question needs to be answered from a remote community energy consumption perspective.

5.2.1 PDR control system

According to the Oxford dictionary, to validate something is "*to prove that something is true*" (Hornby, 2000). Hence, the validation of the PDR control system is a measure of accuracy between what the participating consumers suggest they will do and what they actually did when a PDR trial was carried out. The PDR concept suggests two levels of participatory demand reductions. Therefore, the validation of the system will be the achievement of the required level of VPP from participating consumers in response to a signal generated by the supplier. A representation of how the validation process is approached is shown in Figure 5.7.

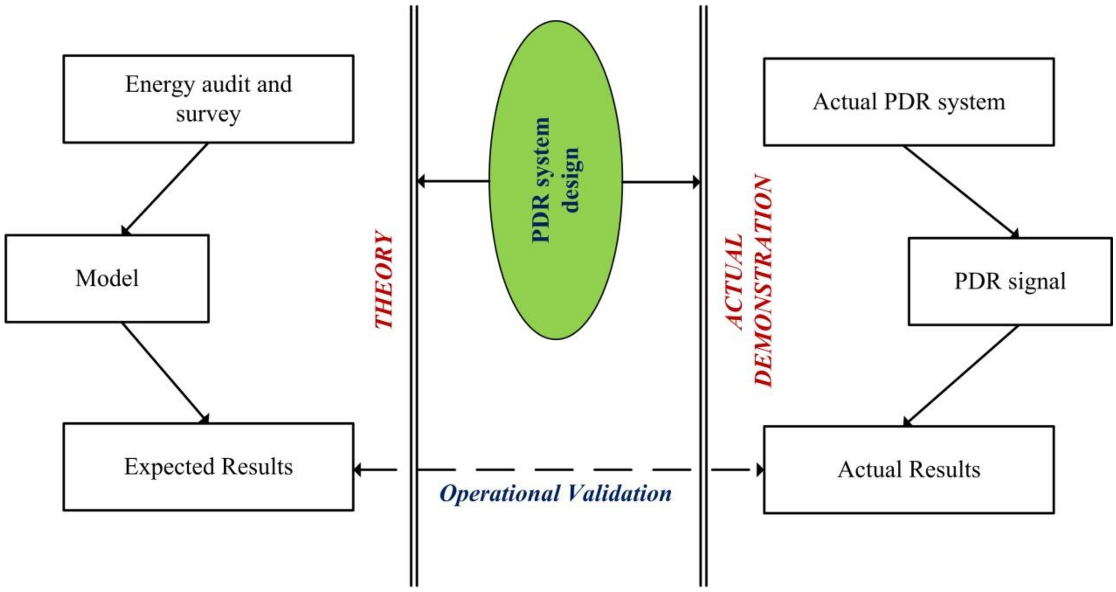


Figure 5.7: PDR system validation approach

The expected results of the participation potential, in response to a particular PDR signal, are calculated by analysing the energy audit and survey data using the equations provided in the PDR model. The reference elements explained in **section 3.5** have to be considered while conducting the surveys. The participants should be made aware of the system concept, they should have understanding as to why the proposed actions are necessary, and they should be given sufficient information on the functioning of appliances at home and the functioning of equipment in the generation sector.

Once participants are informed about the PDR concept and what needs to be done, an actual demonstration needs to be conducted. The result obtained from the actual demonstration has to be statistically analyzed in order to know if a reduction in energy use has been achieved. The result has to be compared with the requested level of VPP and the result expected from the participants, in order to validate the PDR control system. An exact match is unlikely but there should be a rational resemblance to the expected level. The percentage difference between these two results is consequently monitored by the DUF matrices.

5.2.2 Operator control system

To validate the operator control system (OCS), powerhouse operators must endorse the UFCOCS program as a useful tool for managing regular operations as well as constraint situations. The operators have to understand how the program works, how to read the output information on the GUI and must also understand the signalling procedure when it is required. If the operators can visualize the community power system in a broader perspective due to the implementation of UFCOCS, as compared to the initial system that was being practiced, then the OCS will be validated.

In **section 4.2.3**, two survey questionnaires for the powerhouse operators were discussed. The results of these two surveys can be used to validate the OCS. Questionnaire 1 in Figure 4.4 forms the baseline for the comparison. This questionnaire survey monitors the initial situation of the powerhouse management. After the first questionnaire, the UFCOCS is introduced to the operators. The program is explained and the operators are asked to work on it personally. The second questionnaire is then given to acquire their opinion on the working of the UFCOCS and their comparison between the traditional system and the new concept. The percentage of endorsement of the new concept will be the validation of the OCS.

5.3 Fenfushi case study

The survey of essentiality of end-use was conducted during a site visit to the island of Fenfushi from August 2012 to October 2012. A total of 30 households were randomly chosen to complete the survey. The survey was conducted in an informal manner at a time that suited the person taking part in the questionnaire. The person being questioned was one of the 'heads of the household'. During the survey meetings, the three reference design elements were taken into consideration to inform the participating consumers on the PDR concept. The energy audit was carried out along with the adaptability survey for the same 30 households.

The OCS validation survey for the powerhouse operators was also conducted during the initial days of the site visit. The operators were then taught how the system worked, and advised on when and why to carry out the PDR signaling. Once the operators and the participants were clear about the concept, it was time to test the theory and validate the PDR design.

During the survey, the participants were informed that "during the next couple of months, the PDR concept will be practiced and the participants will be getting a message from the powerhouse staff to carry out different PDR levels of energy conservation". Therefore, different constraint scenarios were modeled and exercised during the same period, to analyze how the participants responded to signals generated by the power supplier. These scenarios were created to test different levels of PDR and also the response during different times of the day. The signals sent took the form of text messages sent to the mobile phone of the senior member of the household. The text messages informed them when to reduce the load to either the MCD or SCD level, and when they could start consuming electrical energy as 'Normal'. Due to equipment limitations, there were no separate monitoring devices installed at individual households, so, the load was measured at the powerhouse. This means the measured readings from the powerhouse included the load of the participating households as well as those that were not participating.

5.3.1 Constraint scenario 1 (CS1)

The first PDR test was carried out on 15 September 2012, a Saturday. On this day, the author got the chance to test the concept in regard to an actual constraint situation. The powerhouse staff were working on installing the new 160kW generator (Gen Set 2), and therefore the community load was peaking beyond the overload limit of the generator on load (Gen Set 1). As per normal procedure, the powerhouse staff were ready to start shedding load by disconnecting different areas of the island. However, as per the authors request, the staff agreed to test the response to the PDR signal.

Text message signals to conserve the amount of energy use to the MCD level were sent to the mobile phones of the participating households at 11.00 a.m. The message read as follows:

> "*Due to an emergency work carried out in the powerhouse, the community load needs to be reduced to avoid load shedding. Please reduce the consumption until further notice. Thank you. Powerhouse*

> *Staff* "

Once the generator installation had finished and Gen Set 2 was up and running, a second signal was sent at 2.30 p.m. to the same mobile numbers informing that continuation of Normal load consumption. This message read:

> "*We are pleased to inform you that a new generator has now been installed in the island and is in operation. Your help in managing the community load is highly appreciated. You may now continue with Normal consumption. Powerhouse Staff* "

5.3.2 Constraint scenario 2 (CS2)

The second constraint scenario was designed to test the response from the participants during a time when the load was normally high. The following fictitious scenario was created:

- Fuel delivery had been delayed by a week.
- The community needed to be conservative (MCD level) during times of normally high demand.
- Fuel consumption had to be closely monitored by the power supplier such that the amount of fuel in the bunker could be managed without load shedding.

The initial PDR signal (message) designed to be sent to the participants will read:

> "*We have been informed that the new fuel shipment has been delayed by a week. We need to be conservative in our daily consumption. At the present load we will not be able to manage the amount of fuel we have. Please conserve the use of power until further notice. Thank you. Powerhouse Staff* "

The signal for Normal consumption will read:

> "*Thank you for your co-operation in reducing energy consumption during the last few hours. You may now start consuming electrical power as Normal. Powerhouse Staff* "

5.3.3 Constraint scenario 3 (CS3)

The third constraint scenario was a scenario similar to CS2, but will be carried out on a different day of the week. This test was done because as discussed in **section 4.5.2**, one of the factors that affects the amount of energy being consumed is the day of the week. The same text messages used in CS2 will be used as signals in this scenario.

5.3.4 Constraint scenario 4 (CS4)

The fourth constraint scenario will be a test for the level of response that could be achieved when the participants are asked to reduce consumption to SCD level. The following fictitious scenario was created:

- The fuel delivery has been delayed by a week due to bad weather and there is a possibility of further delay.
- The community has to be updated on the status of fuel delivery and everyone needs to start energy conservation measures
- The fuel consumption rate has to be monitored closely by the powerhouse staff. The fuel consumption has to be strictly maintained within the new tolerance limits calculated as per the new expected delivery date.

There will be three signals generated during this scenario. The first signal will be for MCD level consumption which will be followed by a signal for SCD level consumption. The last signal will be to return back to the ND consumption level.

The initial PDR signal (a text message for MCD level) will read:

> "*We have been informed that the new fuel shipment has been delayed by a week due to bad weather. There is a possibility for further delay. At the present load we will not be able to manage the amount of fuel we have. Please conserve the use of power until further notice. Thank you. Powerhouse Staff* "

The second PDR signal (a text message for SCD level) will read:

> "*The present load suggests that there is work been done to reduce the amount of energy used. However, the load should be further reduced in order to manage the amount of fuel being consumed. Please try to restrict use of appliances to the essential ones only until further notice. Thank you. Powerhouse Staff* "

The signal for Normal consumption will read:

> "*Thank you for your co-operation in reducing energy consumption during these hard times. You may now start consuming electrical power as Normal. Powerhouse Staff* "

5.3.5 Constraint scenario 5 (CS5)

The fifth constraint scenario was designed to test the response from the participants during the evening peak load time. The scenario created was similar to the CS2, except that the time of the PDR signal was different. The PDR signals, or text messages, from CS2 will be will be used in this scenario.

5.4 Summary

This chapter described how the PDR design developed in this thesis will be validated. The electrical power generation, fuel supply and storage system existing on the island of Fenfushi was explained. Fenfushi's power transmission and distribution system was described, along with the powerhouse operation and tariff structure. It was found that the island used to have a flat rate tariff of approximately US$0.4 per kWh until February 2012. Since then, the tariff structure was changed to a bandwidth charge structure.

The thesis concepts and how they will be validated were also explained in the chapter. The first concept to be validated is the PDR control system and the second is the operator control system. The chapter has discussed how the Fenfushi case studies to be carried out for validating the PDR concepts, were designed. The PDR concept was explained to the stakeholders during the initial energy audit and survey stage. The participants were informed about the type of tests that would be carried out and what was expected from them during that time. After the survey, different constraint scenarios were designed by the author. These were discussed in this chapter. The next chapter will present the analysis and the results of the case study carried out in Fenfushi.

CHAPTER 6

RESULTS AND ANALYSIS

"Coming together is a beginning; keeping together is progress; working together is success"

-Henry Ford-

THE previous chapters described a novel real-time feedback control system for a resource constrained power grid that utilized participatory demand response (PDR) from end-users. A case study was conducted by the author on an island in the Maldives, to test the PDR system. The details of the case study were described in Chapter 5.

This chapter presents an evaluation of the PDR system. Firstly, results of the energy audit and survey carried out with the participating households during the case study are discussed in section 6.1. Section 6.2 is the evaluation of customers' responses to the adaptability survey. The reference load curves for Fenfushi are calculated and presented in section 6.3. The response for the constrained scenarios practiced on the island are evaluated and statistically analyzed in section 6.4. Section 6.5 is a comparative analysis of the fuel consumption during the days when PDR was carried out. The powerhouse operator survey has been analyzed along with the validation of the operator control system, in section 6.6. Finally, the chapter is concluded by a summary in section 6.7.

6.1 Energy audit and survey results

The energy audit and survey of Fenfushi island was conducted in August 2012, by the author of this thesis. Since the author is a native Maldivian, there were no difficulties in conversing with the people of Fenfushi, even though the survey forms were prepared in the English language. The author was able to convey the questions to the participants, especially to those who had difficulties understanding English.

6.1.1 Dwelling information

The island of Fenfushi had a lot of new households being built during the time of the survey. However, most of the households were built before the year 2000. Table 6.1 shows the age of the surveyed households.

Table 0.1: Age of surveyed households in Fenfushi

Year built	Number of households	Percentage
After 2005	5	16.67
Between 2001 - 2005	2	6.67
Between 1991 - 2000	12	40.00
Before 1991	10	33.33
Not Sure	1	3.33

One third of the householders that took part in the survey lived in dwellings that were built before the year 1991. Most of the households were built between the years 1991 and 2000. However, according to the household owners, some of these dwellings were rebuilds following the demolition of the old houses that were used by their grandparents.

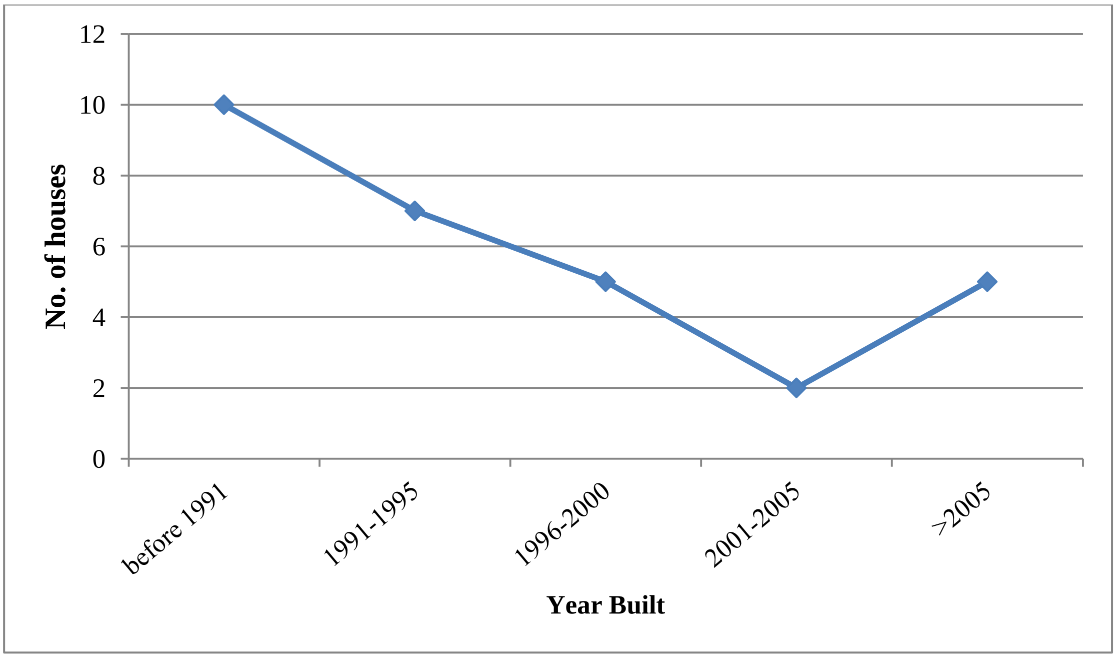


Figure 6.1: Age of the house

The number of people residing in houses built recently is on the rise. This trend can be observed in the Figure 6.1. There was a gradual decline in the number of houses built up until the year 2005, after which the trend has shown an increase.

The number of bedrooms available in the participating households was compared with the 2006 census data for the atoll to which Fenfushi belongs. This comparison, shown in Table 6.2, indicates that half of the surveyed houses had more than four bedrooms while the 2006 atoll census indicated that most of the houses in the atoll had two to three bedrooms. According to the locals of Fenfushi, most of the families tend to reside as an extended family. Consequently, they opt to build separate bedrooms within the boundaries of the same dwelling. Calculations show that the average household occupancy in Fenfushi is 11.7 while the average household occupancy size of the atoll is 6.1, as shown in Table 6.3.

Table 0.2: Comparison of number of bedrooms in the surveyed houses on Fenfushi with that of statistical data for the atoll

No. of bedrooms	Surveyed households		Atoll census (2006)	
	Number	Percent	Number	Percent
1 room	0	0.00	173	16.32
2 rooms	1	3.33	309	29.15
3 rooms	6	20.00	257	24.25
4 rooms	8	26.67	171	16.13
More than 4 rooms	15	50.00	115	10.85

Table 06.3: Average household occupancy statistics

Area	Average household occupancy	Data obtained from
Republic of Maldives	6.5	Census 2006
Atolls	6.1	Census 2006
Male' (Capital island)	7.4	Census 2006
Fenfushi	11.7	Survey calculation

6.1.2 Household plumbing system

Fenfushi does not have a public water supply network. This is true for most of the outer islands in the Maldives. Every household has an open well from which to supply ground water. From the surveyed population, just over 93% of the houses have access to an open well, for manual use during periods when electric water pumps are shut down. In such instances, a "*dhani*[4]" is used to lift water from the well. Figure 6.2 shows a bathroom of a household in Fenfushi, with an accessible open well, a *dhani* and an electric water pump. The inside of the same well is shown in Figure 6.3.

Figure 6.2: A bathroom of a household in Fenfushi showing open well, dhani and the electric water pump

[4] Dhani is the dhivehi name given to a cylindrical pot attached to a long stick (or sometimes a PVC pipe), to lift water from an open well. The cylindrical pot is made from metal sheet and closely resembles cans used for packing powdered dairy milk.

Figure 6.3: Inside of an open well

PVC pipes run from the pump to different areas of the household where running water is required. Survey statistics show that a majority (77%) of the surveyed households have a single water pump, a few (17%) have two pumps, and a small percentage (7%) are without an electric water pump (refer to Appendix A6). Among the surveyed percentage, there were two households that did not have manual access to an open well. These houses needed the operation of an electric water pump as one of their most essential requirements.

6.1.3 Monthly power cost

The island average monthly electricity bill was NZD$109.69 (MVR[5] 1391.67) with a standard deviation of NZD$59.5. The average monthly cost varied between a minimum of NZD$11.82, and a maximum of NZD$236.45. The chart in Figure 6.4

[5] MVR stands for "Maldivian Rufiyaa" which is the official currency used in the Republic of Maldives. The currency conversion was done based on the Bank of Maldives rate on 13 December 2012, which was NZD$ = 12.6877MVR.

illustrates how the average monthly power cost varies for the surveyed population.

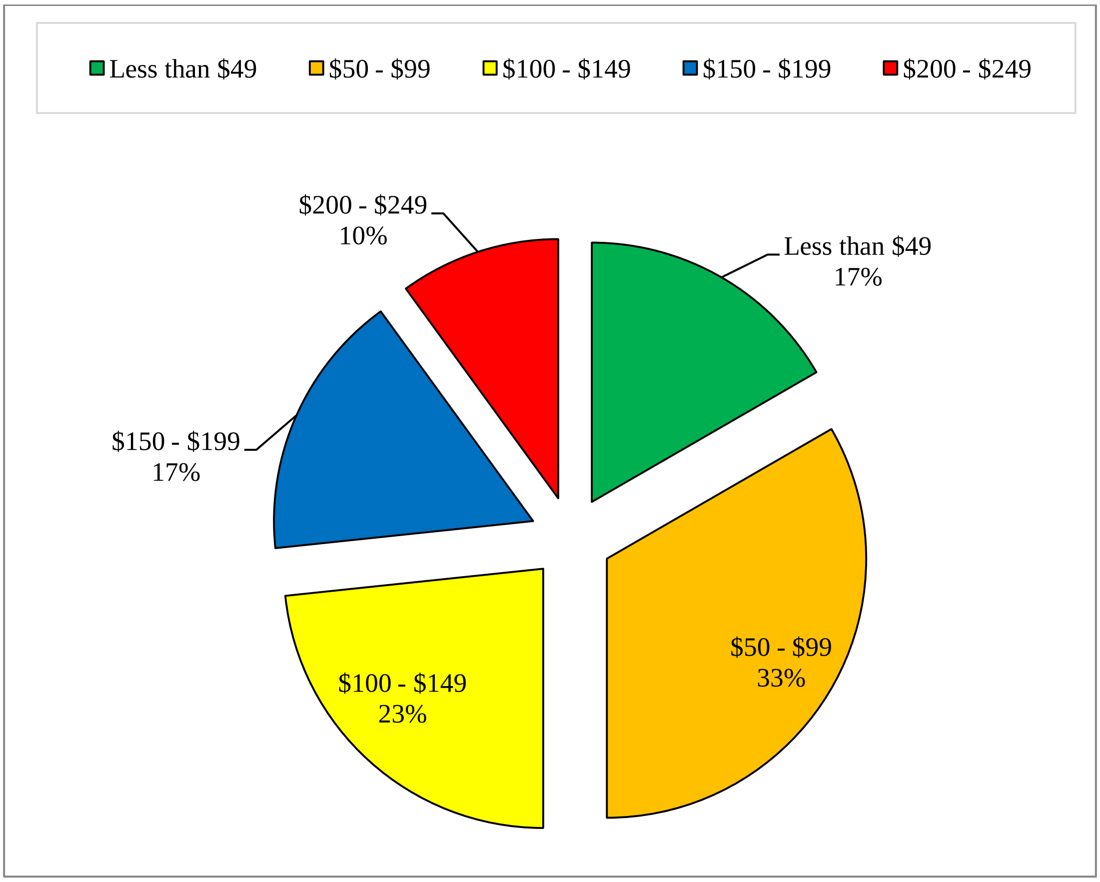


Figure 6.4: Island average of monthly electric power cost

The household power cost is observed to be more related to the level of household occupancy than the number of bedrooms available in the house, and especially to the number of adults than to the other occupants. These relations are shown in the comparisons in Figures 6.5 and 6.6, respectively. A trend line drawn in a scatter plot represents the line of best fit. The value of R^2 represents the level of correlation between the two variables. R^2 is a positive value between *0* and *1*, where a value of *1* represent a perfect correlation (Dunn, 2001). Different researchers may use different interpretations for this value. Table 6.4 shows how the author of this thesis interprets the value of R^2, based on (Dunn, 2001).

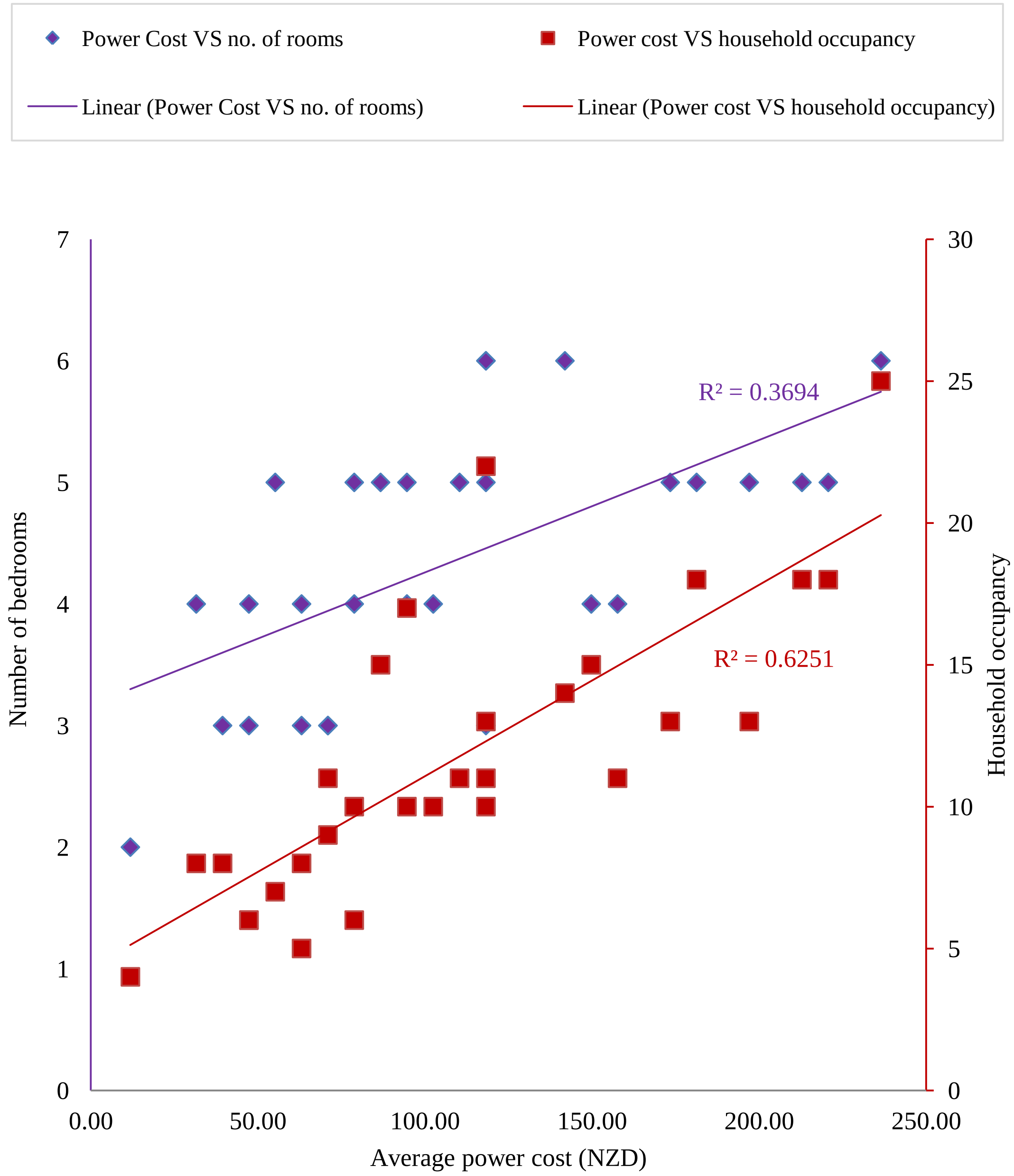


Figure 6.5: Variation of average power cost with number of bedrooms and household occupancy

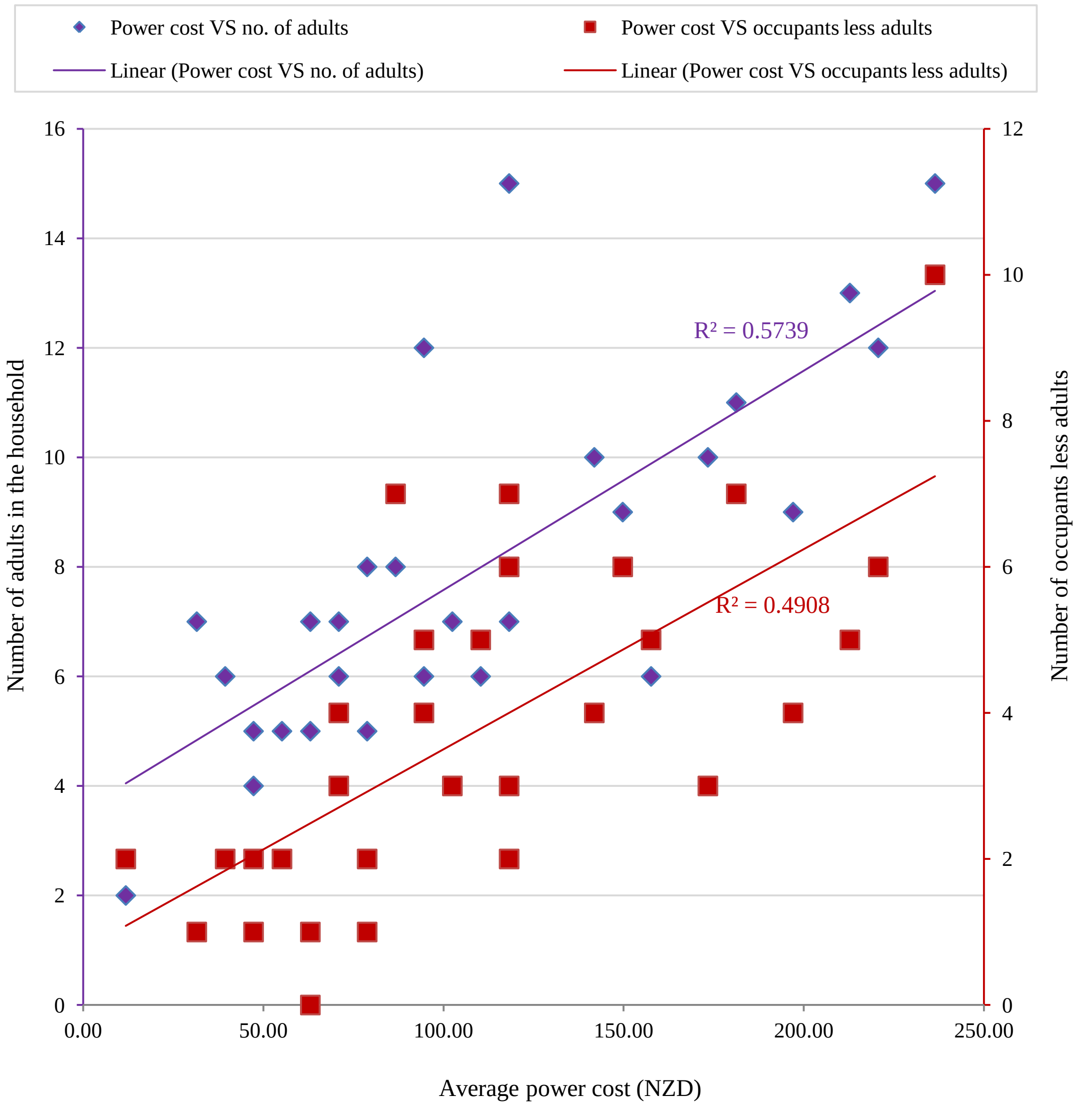


Figure 6.6: Variation of average power cost with adults and with the rest of the occupants

Table 06.4: Descriptive interpretation of the R^2 value

Range for the value of R^2	Descriptive interpretation
0.80 to 1.00	Very strong correlation
0.60 to 0.79	Strong correlation
0.40 to 0.59	Moderate correlation
0.20 to 0.39	Weak correlation
0.00 to 0.19	Very weak correlation

6.1.4 Household energy consumption

The daily load curves for the months of March 2012 to October 2012 were generated using the hourly data log from the powerhouse and are presented in Figure 6.7. The island load never dropped below 40 kW, while the peak load exceeds 90 kW.

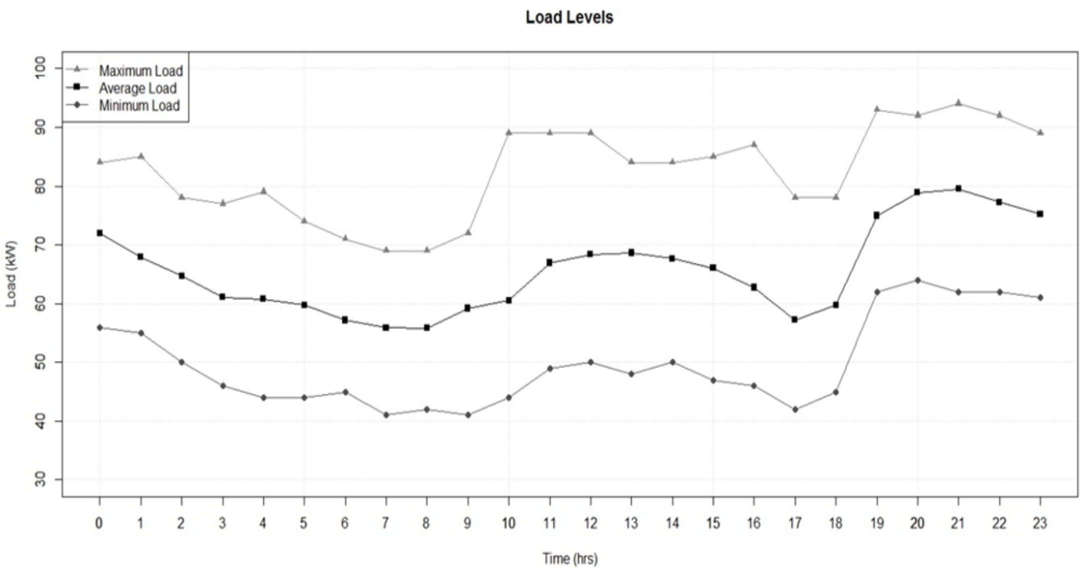


Figure 6.7: Daily loads of Fenfushi island for the months of March 2012 to October 2012

The average load curve indicates an increase in consumption in the morning that reaches a peak near midday, a dip after school and office hours, and then a sharp rise at dinner time that gradually diminishes over the night. The climate in Fenfushi is equatorial and there is heavy reliance on air conditioners and ceiling fans throughout the night to provide comfort in sleeping and to deter mosquitoes.

The saturation rate for the household appliance categories was calculated using **Eq. 8** and is illustrated in Figure 6.8. This shows that all the households had at least one of each of the following appliances: fan, light, electric iron and washing machine. Close to 97% of the households were equipped with fridge/freezers while 93% of the households had TVs and electric water pumps. As much as 77% of the households used electric insect repellents for deterring mosquitoes and other similar insects.

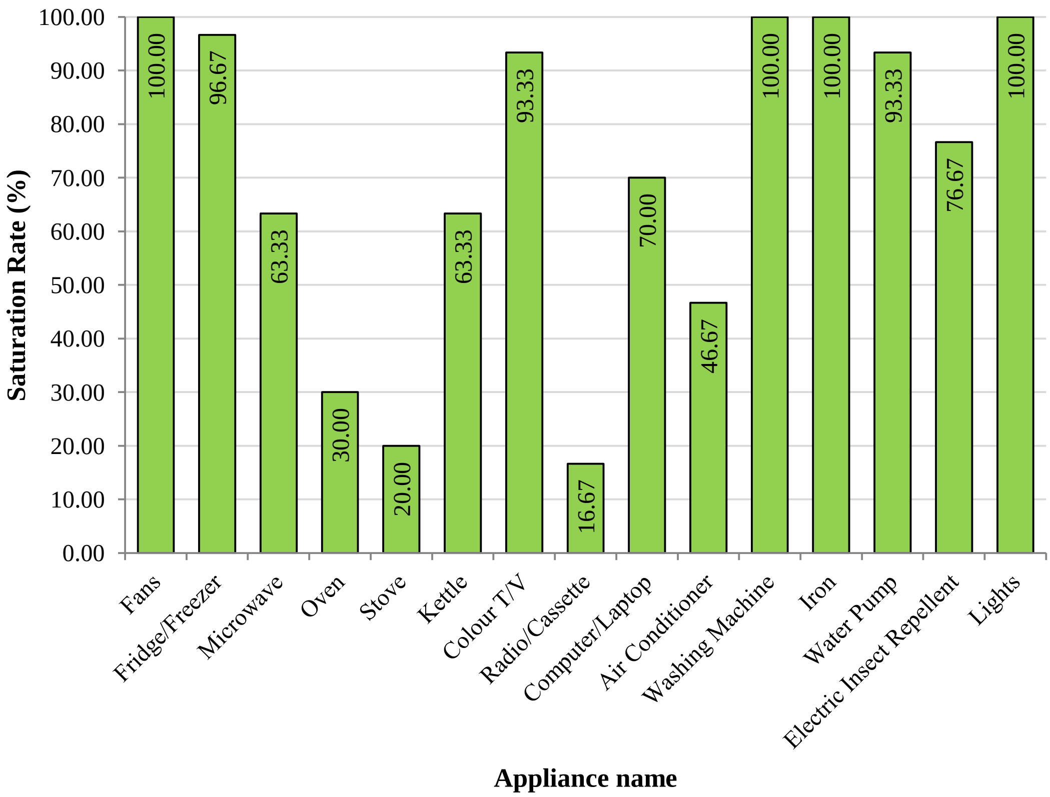


Figure 6.8: Appliance saturation rate for common household appliances

The audit results show that all the households had electric ceiling fans installed while 47% of the households had both fans and at least one air conditioning unit installed, as presented in Figure 6.9. The use of air conditioning devices is on the rise on the island. Electrical energy demand required for running the air conditioners has penetrated the daily energy demand as much as electric fans, despite the fact that more than 50% of the households are without any air conditioners. Figure 6.10 shows that approximately 23% of the daily energy was consumed by air conditioners and is approximately the same as the energy used by electric fans.

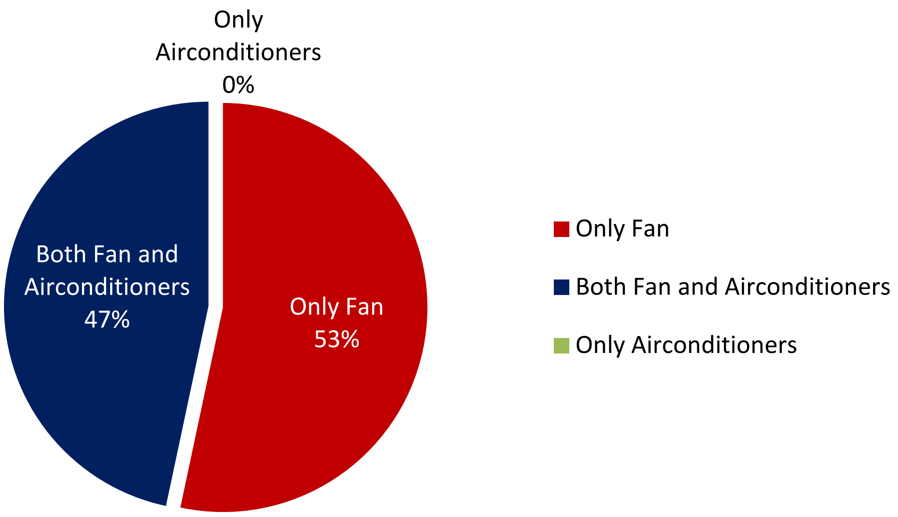


Figure 6.9: Percent of household having fans and air conditioners

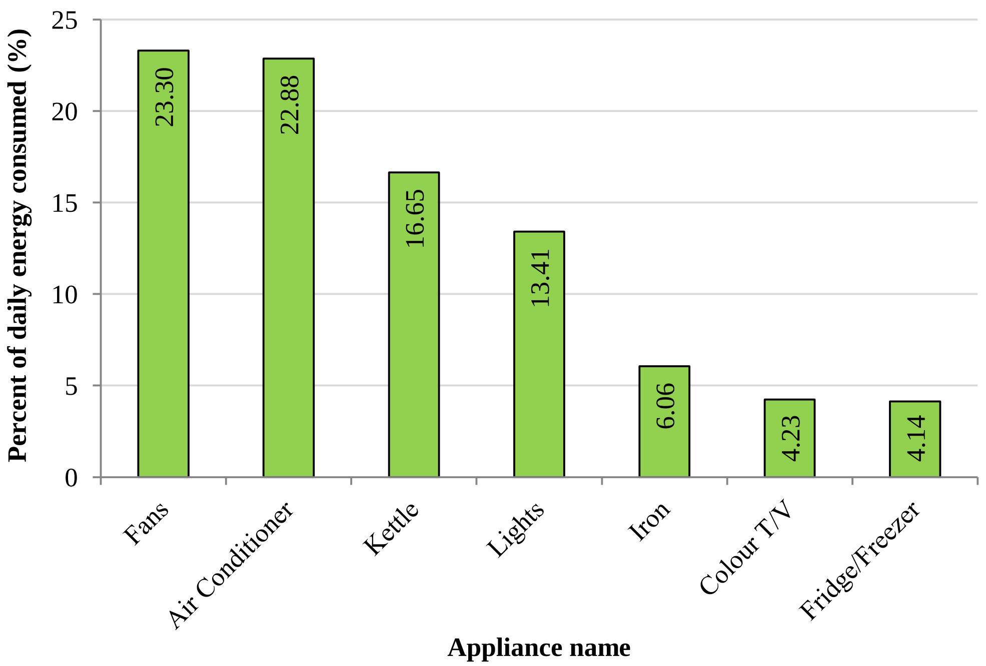


Figure 6.10: Percentage share of daily energy consumed

Figure 6.11 shows the installed load capacity for each of the surveyed households and the average monthly power cost for the same household. The maximum demand of the household has a moderate correlation with the amount being charged for the energy consumed by the household, as shown in Figure 6.12. This analysis is important during the PDR design stage when deciding which households to target first, during a constrained situation where demand response is required.

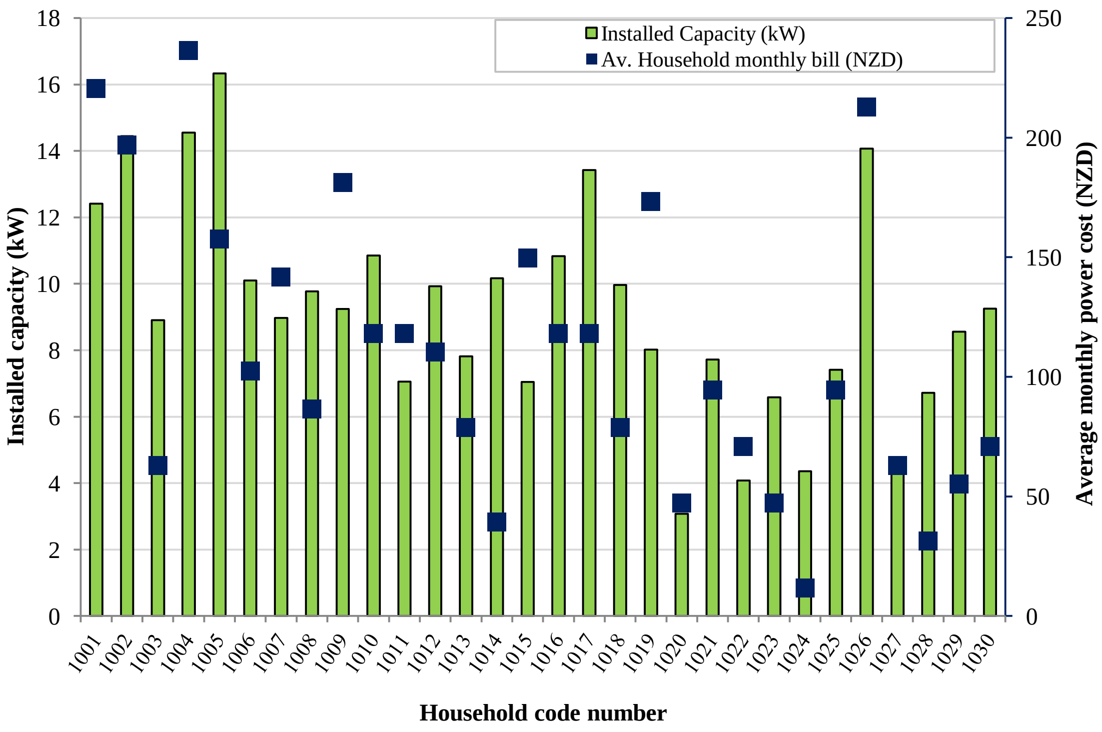


Figure 6.11: Installed capacity and the average monthly power cost, for the surveyed households

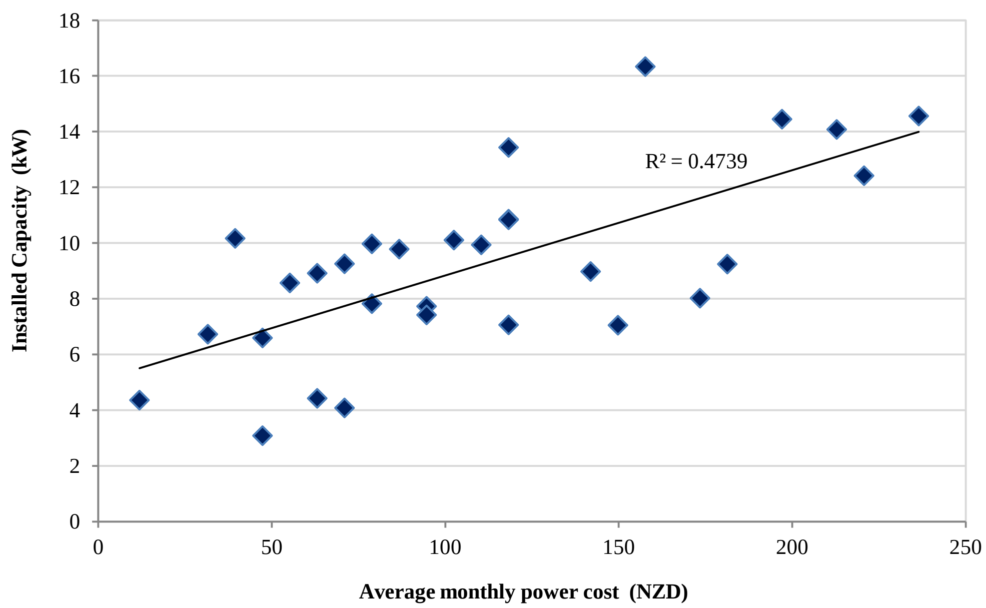


Figure 6.12: Correlation between installed capacity and the average monthly power cost, for the surveyed households

The surveyed population was asked their opinion regarding which household appliance was the most energy consuming. Most agreed that: "*the use of electric ceiling fans*" consumed the most energy. The rest were equally distributed between air conditioners and fridge/freezers, as illustrated in the Figure 6.13. Based on the values presented in Figure 6.10, the majority of people had a clear idea of their most energy consuming appliance. The 20% of the population who identified the air conditioner as the most energy consuming appliance for their household were also correct, because these customers did have air conditioners and the energy consumption of these appliances closely matched the percentage share of the fans, as shown in Figure 6.10.

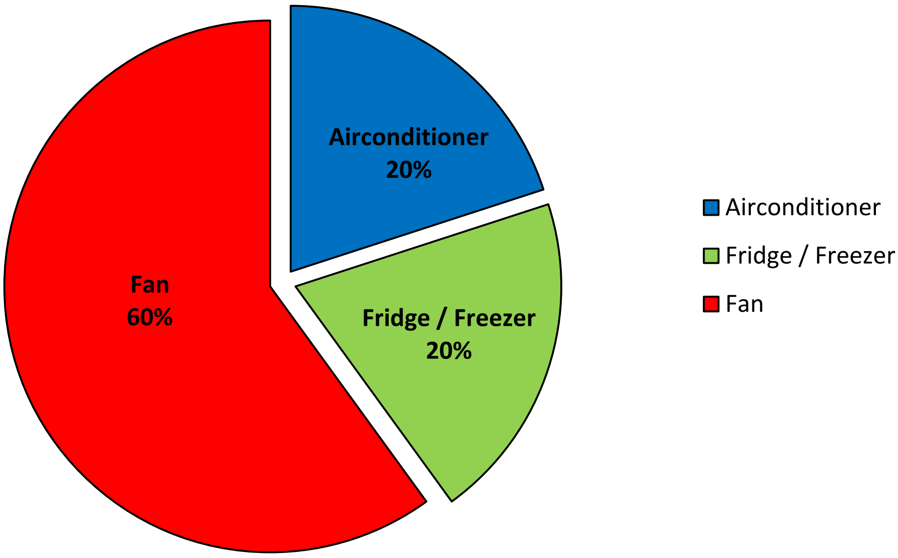


Figure 6.13: Customers' opinions on the appliance responsible for the maximum share of the energy

6.1.5 Customer concerns

The survey had a separate section designed to explore customer concerns regarding price, environmental effects and security of the power supply.

Cost of energy concerns

Figure 6.14 presents the results of the customers' responses to being asked about how concerned they were about their monthly power bills. More than half of the population respondents were "not too concerned". The percentages of Figure 6.14 are interpreted as in Table 6.5.

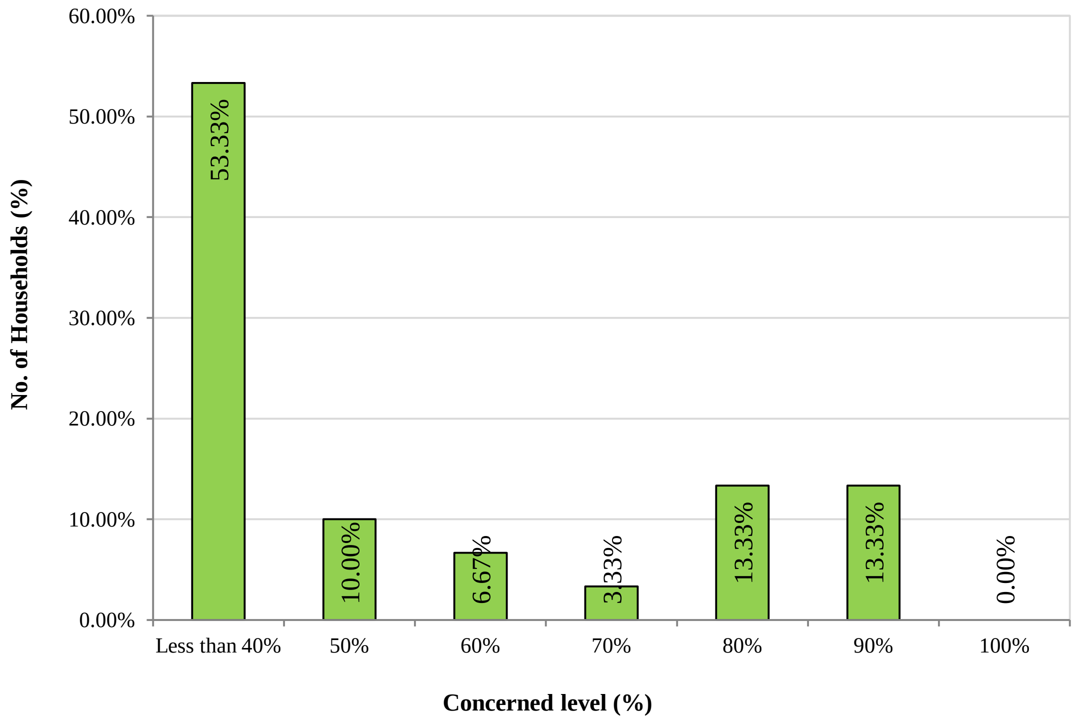


Figure 6.14: Customer response to electricity bill concern

Table 6.5: Descriptive interpretation of the percentage value

Percentage value	Descriptive Interpretation
Less than 40%	Not too concerned
50% - 60%	Concerned
70% - 80%	Very concerned
90% - 100%	Extremely concerned

When customers were asked about energy conservation measures in their household, the response were equally distributed. Half of the surveyed customers said they took conservation measures such as "*turning off appliances (eg. lights, fans) when not in use*". The other half said they do not worry about the energy consumed much and so do not take energy conservation measures seriously.

However, if the cost of energy went up, most of the customers (36.7%) said a price rise of 20% was too high. In addition, Figure 6.15 shows that 30% of the population considered a 10% rise as too high, followed by approximately 27% saying that a 30% rise in the cost of energy is too much. The results suggest that even though half of the customers do not worry about energy conservation during a normal condition, almost everyone is concerned about a rise in the cost of energy of more than 30%.

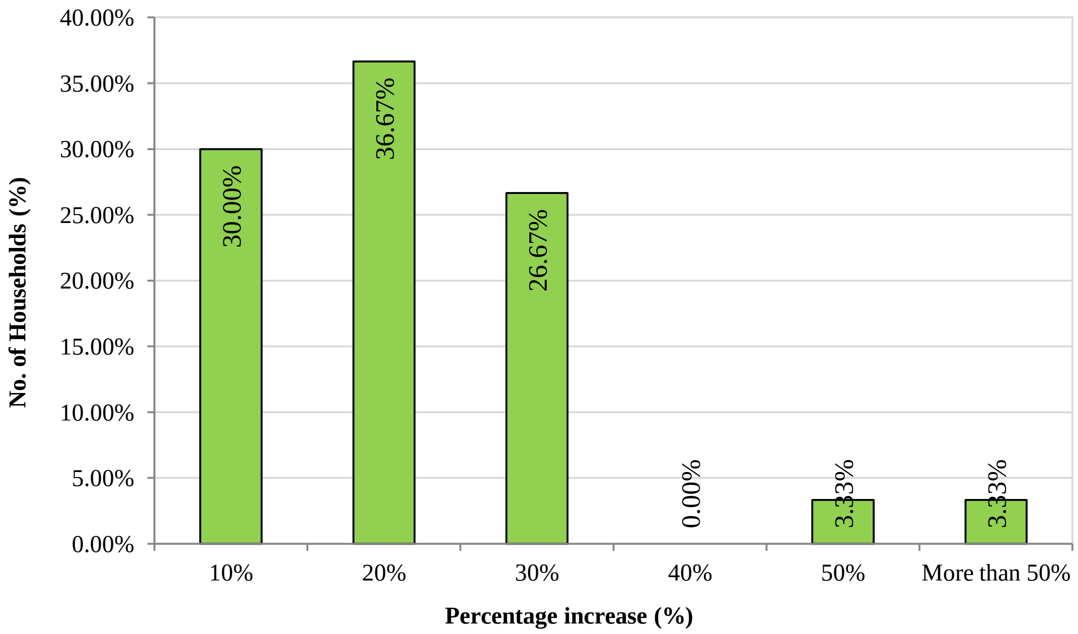


Figure 6.15: Customer response as to what percentage increase in price is considered to be too high

Environmental concerns

The Republic of Maldives, being one of the most vulnerable countries for environmental problems such as global warming and sea-level rise, must have a high level of respect for the environment. However, Maldivians can do little to stop these other than highlight their plight and hope other countries take note and action. They can take local action to ameliorate the effects of climate change and sea level rise. The people should be aware of any incidents regarding damage to the environment, and should have some knowledge of possible solutions. The survey results show that everyone is aware of the type of fuel being used by the powerhouse for power generation, and they are also aware of how the fuel is being transported to the island. When customers were asked if they knew about any oil spill incidents that occurred on the island, half of the population said there had not been any such incidents, as shown in Figure 6.16. However, 17% of the customers said that they knew of an incident that actually happened. According to them, there was a "*leak in one of the main fuel tanks, but don't have much detail*". A third of the population did not know if there had been any oil spill incidents.

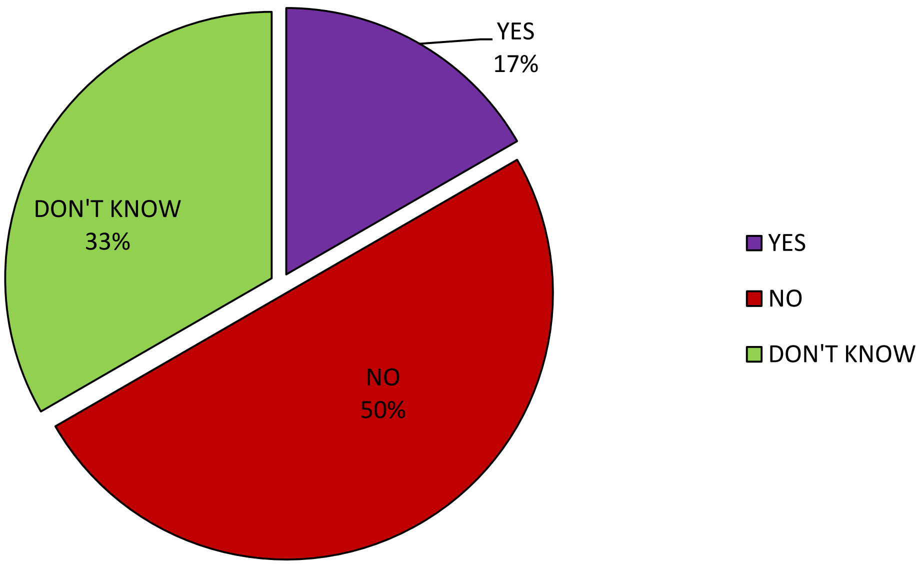


Figure 6.16: Customer response to their knowledge of any oil spill incidents

However, a majority of the population considers smoke and sound as forms of pollution, as illustrated in Figure 6.17. The powerhouse was located not far from the island community as seen in the map in Figure 5.6. The powerhouse was not built with any technology that minimizes the emission of soot, let alone smoke, into the atmosphere. Neither the powerhouse building nor the generator room was built to minimize the sound from the generators. Approximately 37% of the population had concerns about carbon dioxide (CO2). The reason for a lower percentage for CO2 concern reflects the knowledge and the level of awareness among the island population about the emission and effects of CO2. Other comments on pollution included that it "*generates harmful waste*" and was "*too close to public amenities*".

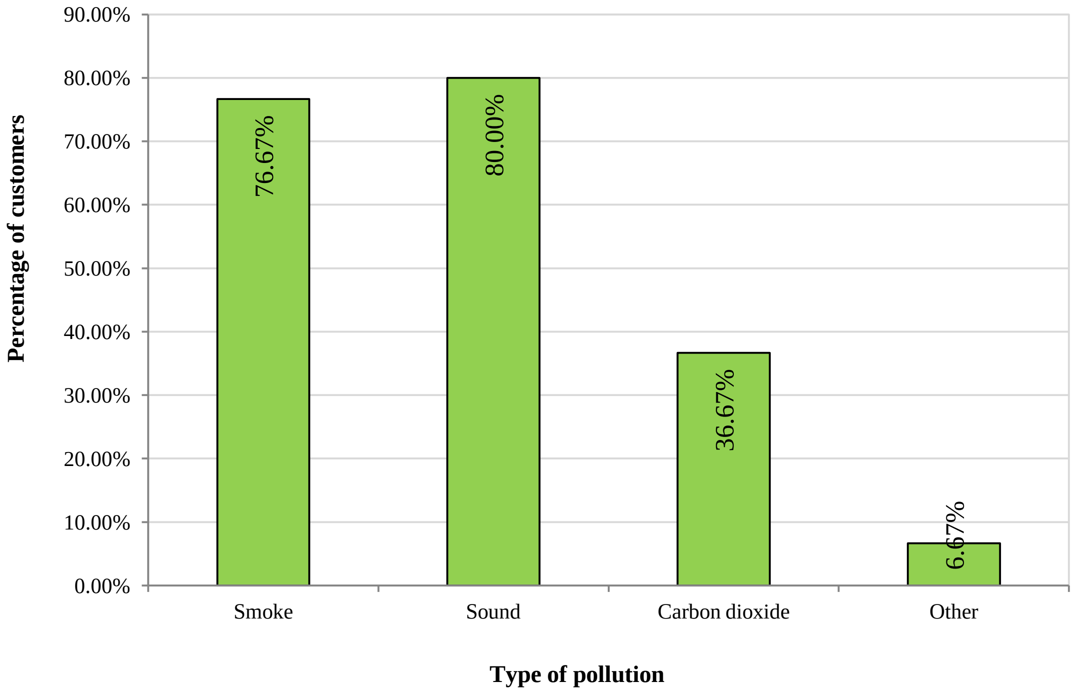


Figure 6.17: Types of pollution affecting customers, due to power generation

Electrical energy security concerns

In the months prior to the case study period, Fenfushi had experienced frequent power failures. According to the powerhouse staff, these power failures were mainly due to generator overload. When the surveyed population was asked about what they knew about the reason for the power failure, more than half of the customers had no idea what had caused the failure, as presented in Figure 6.18. Of the population, 23% of people agreed on either overload problems or maintenance related problems, while 17% of the customers thought it was related to fuel problems. The results show that the customers had very little knowledge about what is happening inside the powerhouse. It also implied that Fenfushi had no proper feedback mechanisms that can inform the community about powerhouse operational difficulties.

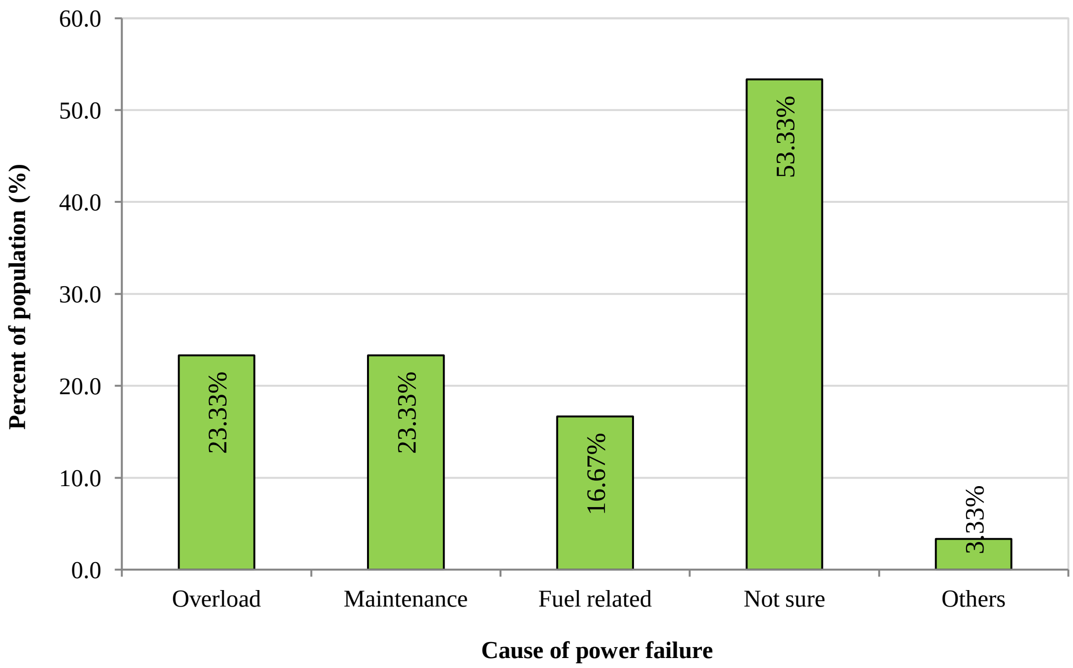


Figure 6.18: Customers' opinions on the reasons for power failures

Customers were asked how well they understood the operation of the powerhouse and how well informed they are about a power failure when it happens. They were asked to choose a percentage value starting from 10% to represent "Not at all" up to 100% which represented "Understand completely/Fully informed". The responses obtained are presented in Figure 6.19.

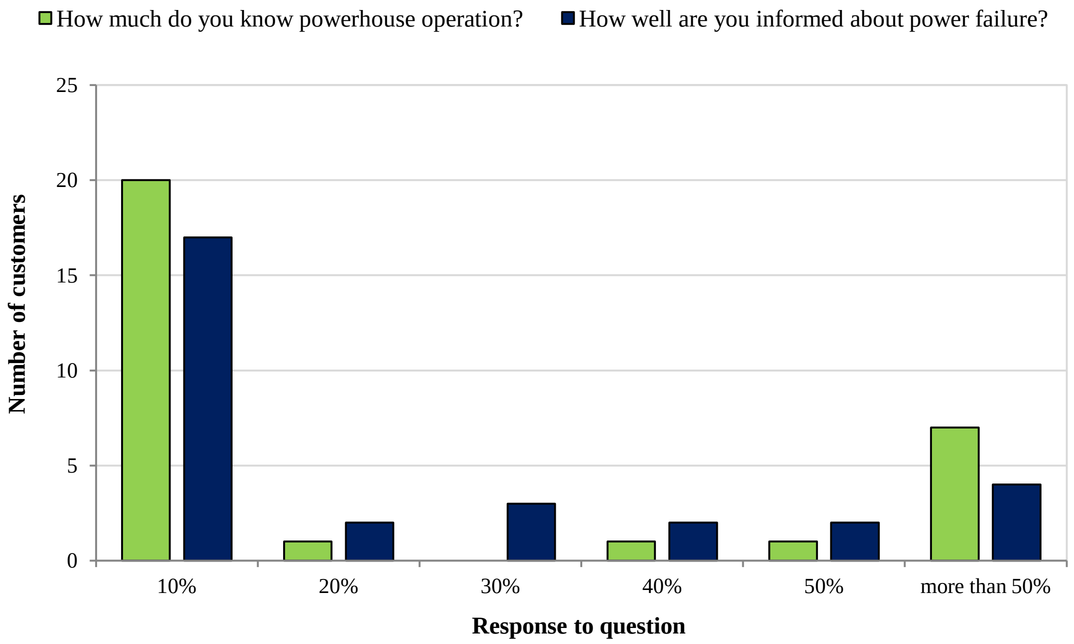


Figure 6.19: Customers' responses to powerhouse operation

The results confirm that customers had little knowledge about the work carried out in the powerhouse. There had been no feedback supplied to customers regarding power failures or any other issues faced by the powerhouse. During the survey, most of the customers replied, "*we only know about what happened when we either go to the powerhouse and ask, or sometimes we call one of the staff on their mobile phone*".

Concern for the security and reliability of the electrical power was very high within the population. However, being a remote community, there were high risks involved in generating electricity from a non-renewable source such as diesel. Customers were asked about the number of power cuts they could tolerate during a situation when the power generation has to be constrained. The results presented in Figure 6.20 show that 40% of customers were ready to tolerate up to a maximum of three power cuts per week, while 23% of customers said that they were ready to accept one daily power cut during emergency (constrained) situations, however, this should not be more than one hour. When asked about the duration for a single power cut among the rest of the population, 60% of them said that the power cut should not be more than two hours, as shown in Figure 6.21.

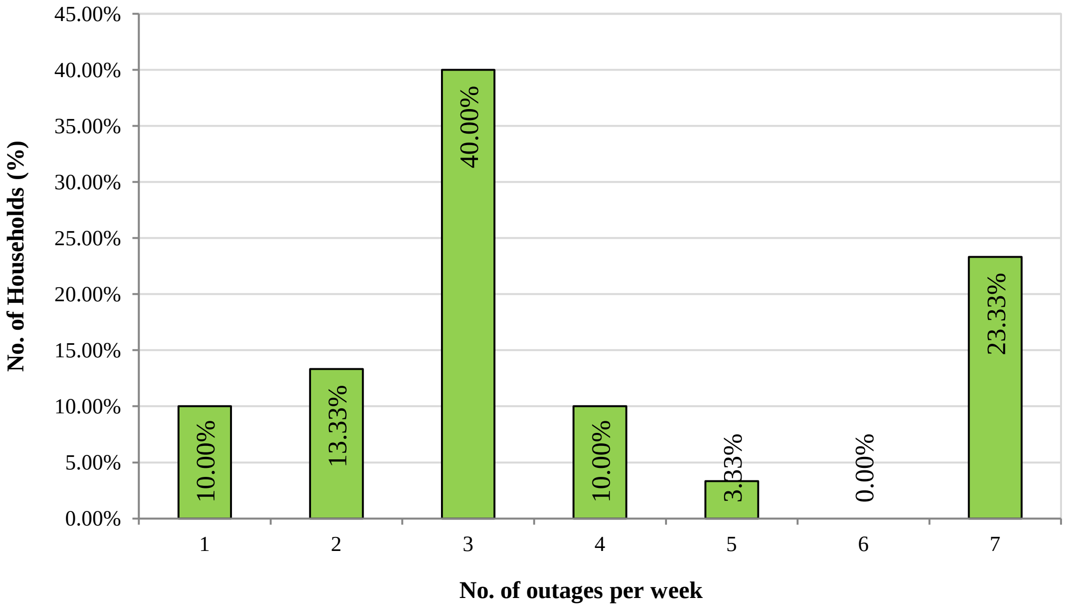


Figure 6.20: Maximum power outages acceptable during a constrained situation

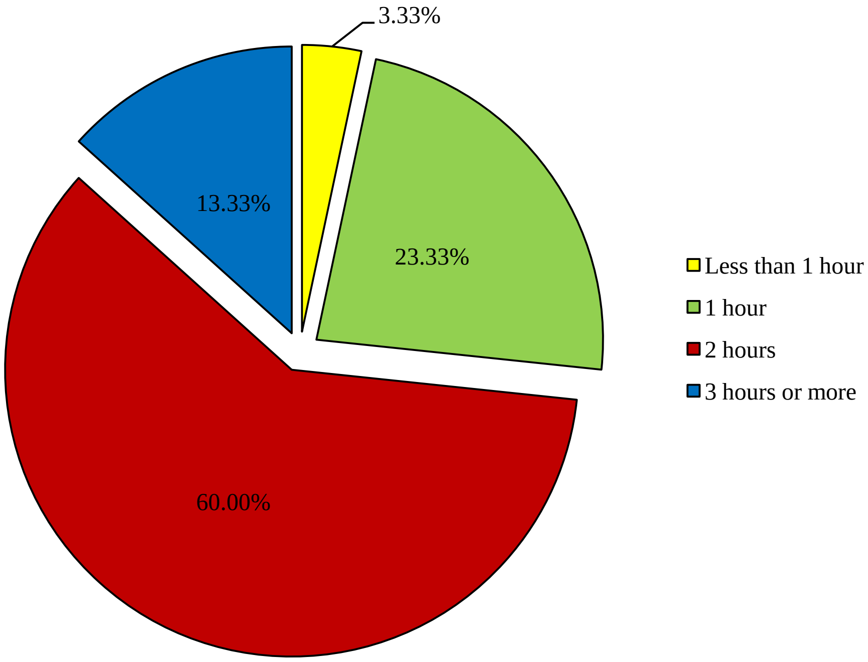


Figure 6.21: How long is too long for a single power cut?

6.2 Energy use during power generation shortage

The adaptability survey also concentrated on depicting what customers would do during an energy constrained situation. This is category eight of the adaptability survey and has been explained in **section 4.2.2**. To classify household appliances into *deferrable*, *optional* and *essential*, customers were first asked about the appliances that could be stopped or their use deferred during a constrained situation. In response to this question, everyone answered with air conditioners, electric irons, washing machines and ovens, as presented in Figure 6.22. Considering the accessibility of water manually drawn from an open well, 60% of the customers responded that they could stop using electric water pumps until the end of the constrained situation, as a participatory conservation measure. As many as 82% of customers also agreed on turning off television sets during the constrained situation period.

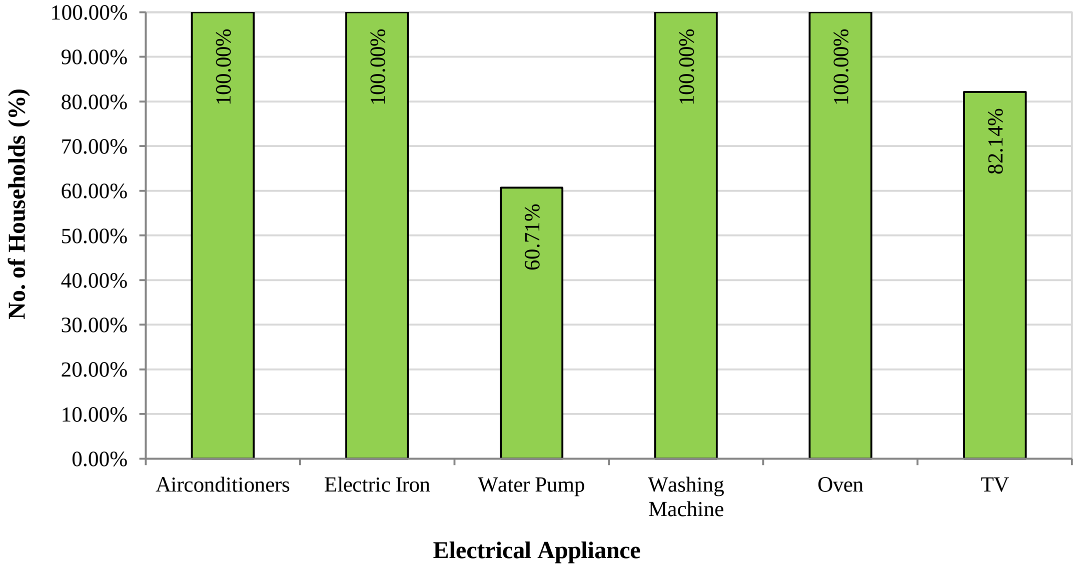


Figure 6.22: Appliances that can be stopped during a constrained situation

The next question concentrated on the amount of reduction that was likely to be achieved from restricting the use of electric fans and lights. Figure 6.23 presents the customers' responses as to the maximum number of lights that would be used during an energy constrained period.

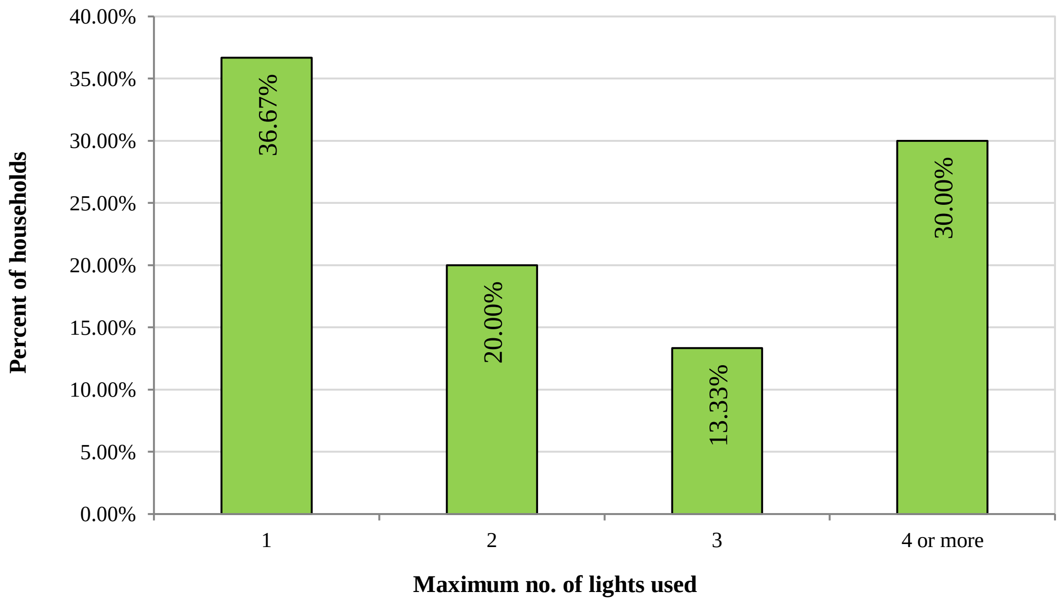


Figure 6.23: Customers' responses as to the maximum number of lights used in a constrained period

The results show that approximately 37% of customers agreed on minimizing the use of lighting to a single light source. However, 30% of the customers said they would consider the participatory conservation measures but they could only reduce the number of lights being used to four or more. These customers were mostly from houses with at least four bedrooms and consider it necessary to have at least one light in every bedroom.

Customers were also asked what percentage reduction they could achieve in the use of electrical fans during the time of a constraint. The results presented in Figure 6.24 show that more than half of the population could achieve a reduction of more than 60%, while another 30% said they were able to reduce the use of electrical fans by up to half of what they use normally.

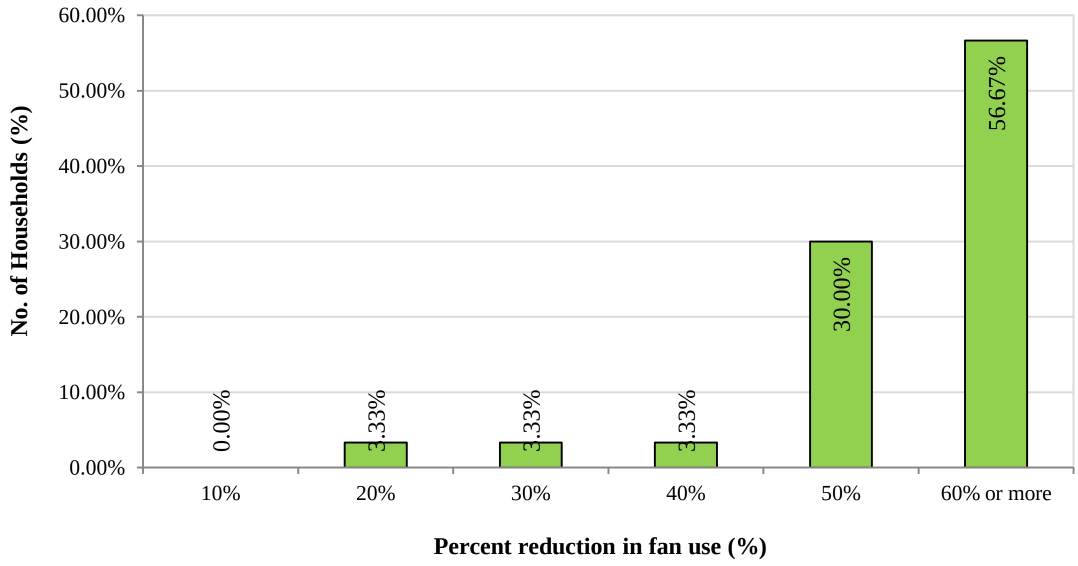


Figure 6.24: Customer response to reduce fan use during a constraint

As PDR methodology requires the understanding of what the most important appliances for the customers are, they were asked to categorize which appliances they considered the most essential. Almost everyone needed to keep their fridge/freezer running, while 13% of the customers also recommended having the water pump running, as shown in Figure 6.25.

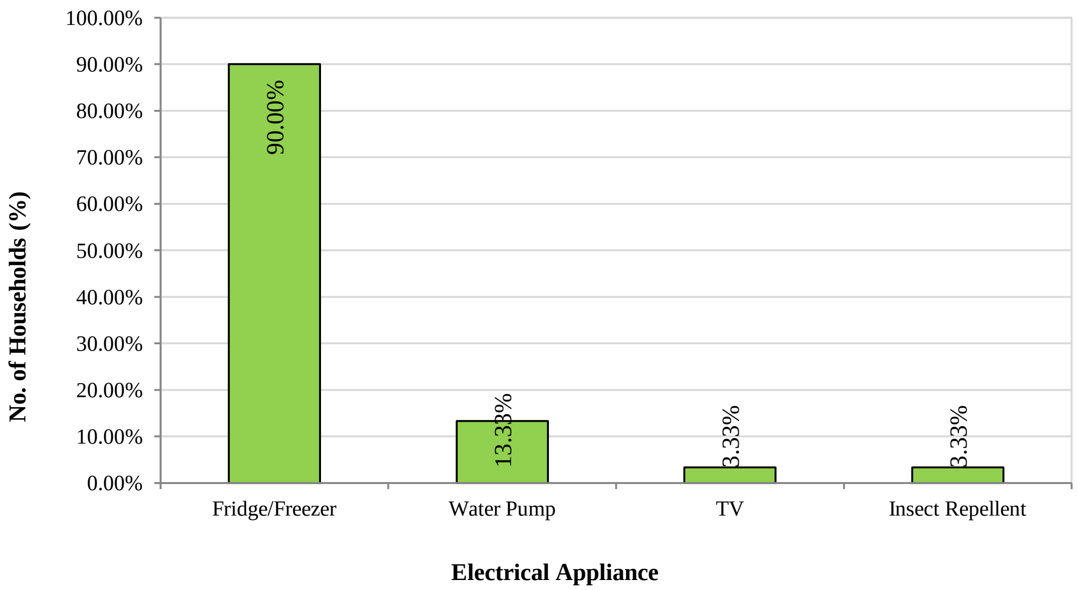


Figure 6.25: Customers' responses as to what their most essential appliances are

6.3 Reference load curves for Fenfushi

To obtain the reference load curves for Fenfushi, the hourly variation factors (HVFs) first had to be estimated using the information obtained by the energy audit and survey. Using the HVF table given by (Gönen, 1986) as a guide, which is presented in Appendix A1, and comparing it with the behavior of the people living in Fenfushi, the HVF for the commonly utilized appliance categories were calculated and are presented in Table 6.6. The graph in Figure 6.26 shows how the HVFs of some of these appliance categories vary with time.

Table 6.6: Hourly variation factors estimated for Fenfushi

Time	Fan, Lights and Misc	Microwave	Oven	Stove	Kettle	TV	Radio	Computer/ Monitor/ Laptop	Air Conditioner	Washing Machine	Electric Iron	Insect Repellent	Satellite Decoder	Fridge/ Freezer	Electric Water Pump
00:00	0.22	0.00	0.00	0.00	0.03	0.03	0.00	0.00	0.25	0.00	0.00	0.25	0.00	0.23	0.09
01:00	0.22	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.25	0.00	0.00	0.25	0.00	0.22	0.06
02:00	0.20	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.25	0.00	0.00	0.25	0.00	0.20	0.05
03:00	0.18	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.24	0.00	0.00	0.25	0.00	0.19	0.04
04:00	0.19	0.00	0.00	0.00	0.02	0.00	0.00	0.00	0.22	0.00	0.00	0.25	0.00	0.18	0.05
05:00	0.21	0.00	0.00	0.00	0.03	0.00	0.00	0.00	0.20	0.00	0.01	0.25	0.00	0.18	0.09
06:00	0.23	0.03	0.00	0.00	0.04	0.00	0.01	0.00	0.17	0.00	0.03	0.25	0.00	0.18	0.12
07:00	0.20	0.09	0.00	0.00	0.08	0.00	0.01	0.00	0.13	0.00	0.06	0.25	0.00	0.19	0.13
08:00	0.18	0.09	0.00	0.06	0.12	0.00	0.01	0.09	0.09	0.03	0.06	0.00	0.00	0.20	0.15
09:00	0.16	0.11	0.00	0.08	0.13	0.14	0.01	0.10	0.05	0.05	0.03	0.00	0.00	0.20	0.15
10:00	0.13	0.00	0.02	0.03	0.14	0.16	0.01	0.14	0.04	0.09	0.03	0.00	0.00	0.20	0.17
11:00	0.15	0.00	0.03	0.10	0.13	0.16	0.01	0.15	0.03	0.13	0.02	0.00	0.00	0.21	0.18
12:00	0.17	0.07	0.00	0.09	0.12	0.13	0.00	0.14	0.05	0.12	0.00	0.00	0.00	0.21	0.16
13:00	0.18	0.06	0.00	0.03	0.13	0.13	0.00	0.14	0.07	0.11	0.00	0.00	0.00	0.22	0.15
14:00	0.20	0.02	0.03	0.00	0.12	0.08	0.01	0.13	0.11	0.08	0.00	0.00	0.00	0.23	0.14
15:00	0.22	0.01	0.05	0.00	0.11	0.06	0.00	0.09	0.12	0.05	0.03	0.00	0.00	0.23	0.13
16:00	0.21	0.06	0.06	0.00	0.11	0.00	0.00	0.06	0.12	0.03	0.05	0.00	0.00	0.23	0.12
17:00	0.20	0.04	0.05	0.03	0.09	0.08	0.00	0.03	0.09	0.00	0.08	0.00	0.00	0.23	0.10
18:00	0.18	0.01	0.01	0.07	0.10	0.12	0.01	0.04	0.09	0.00	0.05	0.25	0.25	0.23	0.11
19:00	0.22	0.01	0.01	0.05	0.12	0.16	0.01	0.07	0.15	0.00	0.02	0.25	0.25	0.24	0.13
20:00	0.22	0.09	0.00	0.02	0.12	0.19	0.01	0.03	0.17	0.00	0.00	0.25	0.25	0.24	0.08
21:00	0.23	0.00	0.00	0.00	0.05	0.21	0.01	0.04	0.21	0.00	0.00	0.25	0.25	0.24	0.08
22:00	0.23	0.00	0.00	0.00	0.02	0.18	0.01	0.02	0.22	0.00	0.00	0.25	0.25	0.22	0.05
23:00	0.22	0.00	0.00	0.00	0.03	0.08	0.00	0.02	0.24	0.00	0.00	0.25	0.25	0.22	0.07

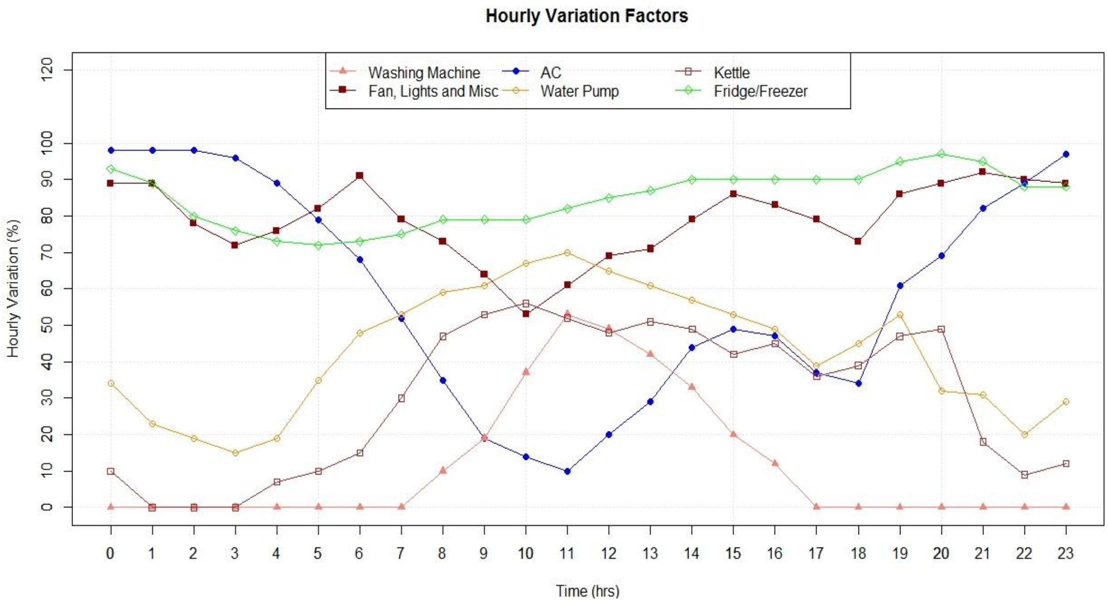


Figure 6.26: Hourly variation factors for some appliance categories

The reference curve for normal demand (ND) can now be calculated using **Eq. 9**, where:

- $F_i(t)$ is obtained from Table 6.6
- s_i has been presented in Figure 6.8
- C for Fenfushi is 120 (total number of households)
- ADD_i is obtained from the graph in Appendix A2

Similarly, the reference curves for medium constrained demand (MCD) and severely constrained demand (SCD) can also be calculated using **Eq. 10** and **Eq. 11**, respectively. The values for $F_{mi}(t)$ and $F_{ei}(t)$ have been obtained using the adaptability survey results presented in **section 6.2**. Figure 6.27 illustrates the three reference load curves generated for Fenfushi.

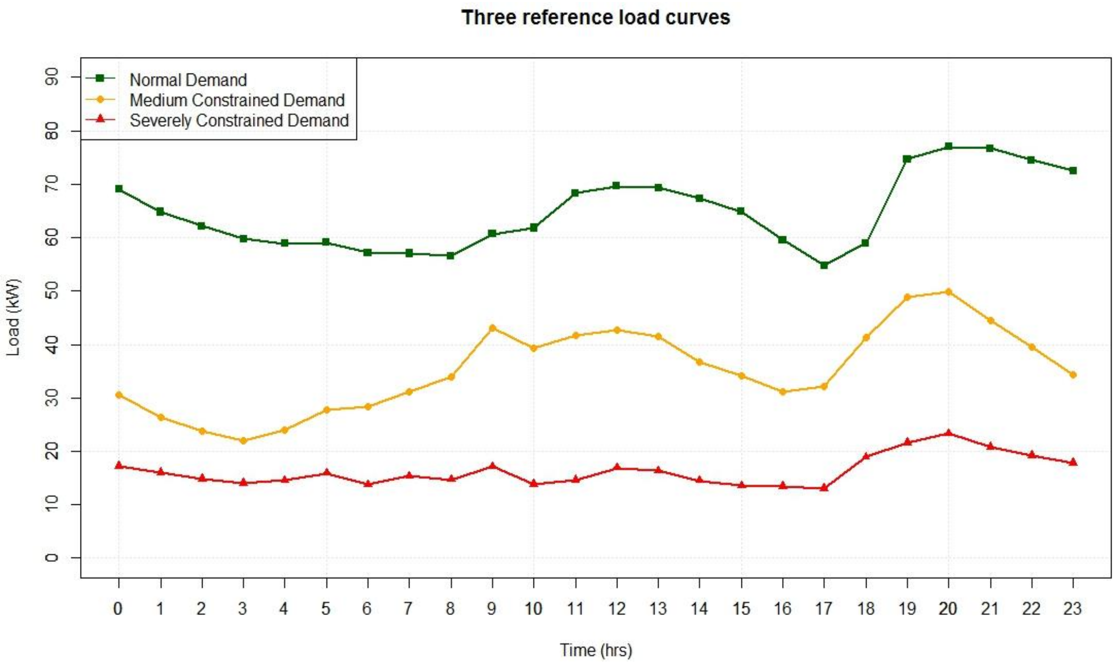


Figure 6.27: Reference load curves for Fenfushi

6.4 PDR from resource constrained scenarios

This section presents a statistical analysis of the participatory demand response carried out on Fenfushi. All the scenarios created for validating the PDR system have been discussed in **section 5.3**. The statistical computing software R[6] used to analyze the results.

6.4.1 Constraint scenario 1 (CS1)

The highlights of CS1 are:

- PDR was carried out on Saturday, 15 September 2012.
- The situation was a real constraint situation, not a fictitious scenario. There was work being carried out at the powerhouse to install a new generator.
- The signal sent was labelled as an "Emergency" situation.

[6] http://www.r-project.org/

- The PDR signal (text message) to conserve energy to MCD level was sent at 11.00 a.m.

- The ND consumption signal (text message) was sent at 2.30 p.m.

The boxplot shown in Figure 6.28 presents the hourly load of all Saturdays logged during the period from August 2012 to October 2012. These three months are the transition time between two monsoons and hence the climate is different from the rest of the year. The green shaded area in the figure represents the time when PDR was carried out.

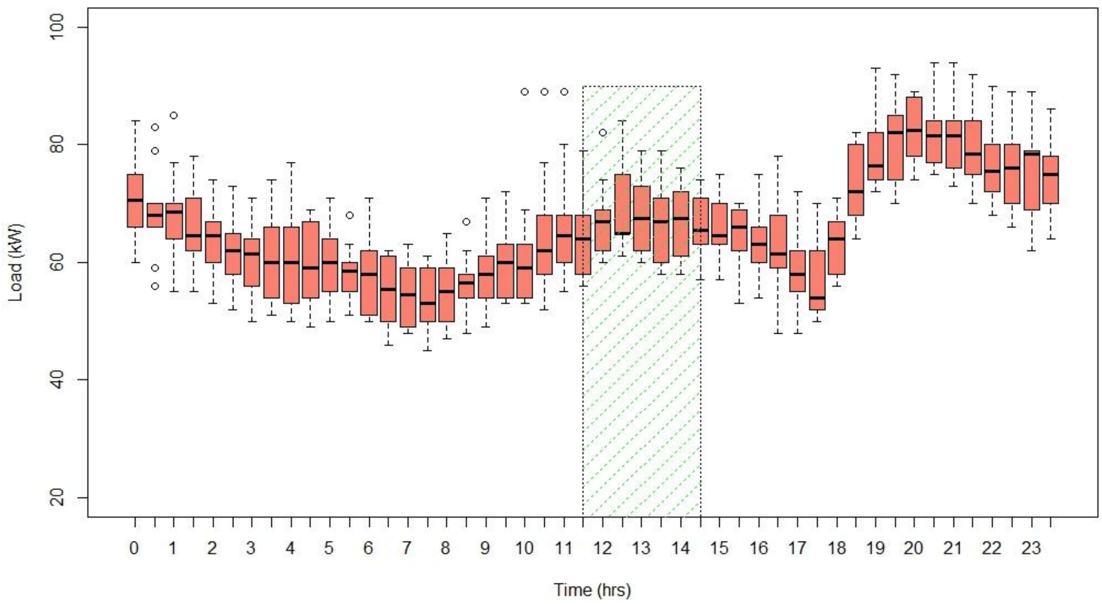


Figure 6.28: Boxplot for hourly load variation on Saturdays, showing the time of PDR for CS1

The boxplot shows a trend in the load variation that can, in general, be modelled by the equation:

$$L(t) = a_0 + a_1 \sin(2\pi t) + b_1 \cos(2\pi t) + a_2 \sin(2\pi 2t) + b_2 \cos(2\pi 2t) + a_3 \sin(2\pi 3t) + b_3 \cos(2\pi 3t) + c_1 DMCD(t) + c_2 DSCD(t) + \varepsilon(t) \quad \textbf{Eq. 23}$$

where *L(t)* is the load in kilo-watts (kW), a_0 is the y intercept, a_1, b_1, a_2, b_2, a_3, b_3, c_1 and c_2 are all coefficients, of which c_1 and c_2 are the coefficients of the time when demand response is carried out, *DMCD* is a binomial dummy variable taking the value '1' during the time of MCD, and *DSCD* is a binomial dummy variable taking the value '1' during the time of SCD, otherwise these two variables take the value '0', and ε is the error.

Figure 6.29 shows the comparison of load for the CS1 DR day and the average for all Saturdays. The load for CS1 suddenly increased at 10.00 a.m. due to work being carried out in the powerhouse to install a new generator. The generator on load, Gen Set 1 (80kW), was operating in an overload condition from 10.00 a.m. until around 11.00 a.m. Once the PDR signal was sent, the load dropped down close to 70kW irrespective of the work carried out in the powerhouse.

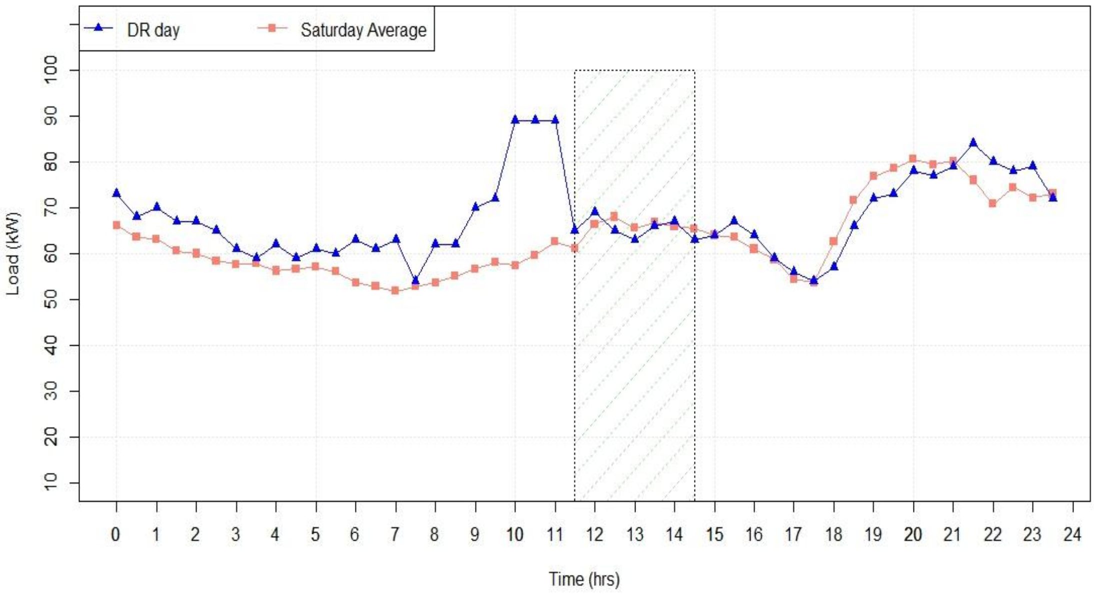


Figure 6.29: Load curves for CS1 and average for Saturdays

When **Eq. 23** is applied to CS1, the value of *DMCD(t)* is '1' during the time when PDR was carried out on 15 September 2012, while *DSCD(t)* remains '0' throughout. The value of the coefficient c_1 is the statistical difference in load between the time of PDR and the rest of the days. Table 6.7 presents the estimation results for the model created using **Eq.23** for CS1.

Table 6.7: Estimation results for the CS1 analysis

Coefficient	*Estimate value*	*Standard error*	*Significance**	*95% confidence interval*	
				Lower bound	*Upper bound*
a_0	66.1213	1.4877	0.0001	63.812	68.6874
a_1	-7.2011	0.3517	0.0001	-7.891	-6.5033
a_2	-3.4607	0.3525	0.0001	-4.158	-2.7659
a_3	-1.8777	0.353	0.0001	-2.603	-1.196
b_1	4.4308	0.3569	0.0001	3.742	5.147
b_2	3.7675	0.3549	0.0001	3.087	4.4726
b_3	-3.6825	0.353	0.0001	-4.365	-2.9776
c_1	-5.0324	2.3092	0.033	-9.672	-0.6082

**the estimated value is significant at 95% if this value is less than 0.05*

The estimation of c_1 for the model shows that the load comparatively decreased by 5.03kW during the time when PDR was carried out.

6.4.2 Constraint scenario 2 (CS2)

The highlights of CS2 are outlined below:

- PDR was carried out on Sunday, 23 September 2012.
- The scenario was that fuel delivery had been delayed by a week and the community needed to conserve energy use during periods of normally high demand.
- The signal to conserve energy to MCD level was sent at 1.00 p.m.
- The ND consumption signal was sent at 4.30 p.m.

The boxplot shown in Figure 6.30 presents the hourly load of all Sundays logged during the period from August 2012 to October 2012. The shaded area in the figure represents the time when PDR was carried out.

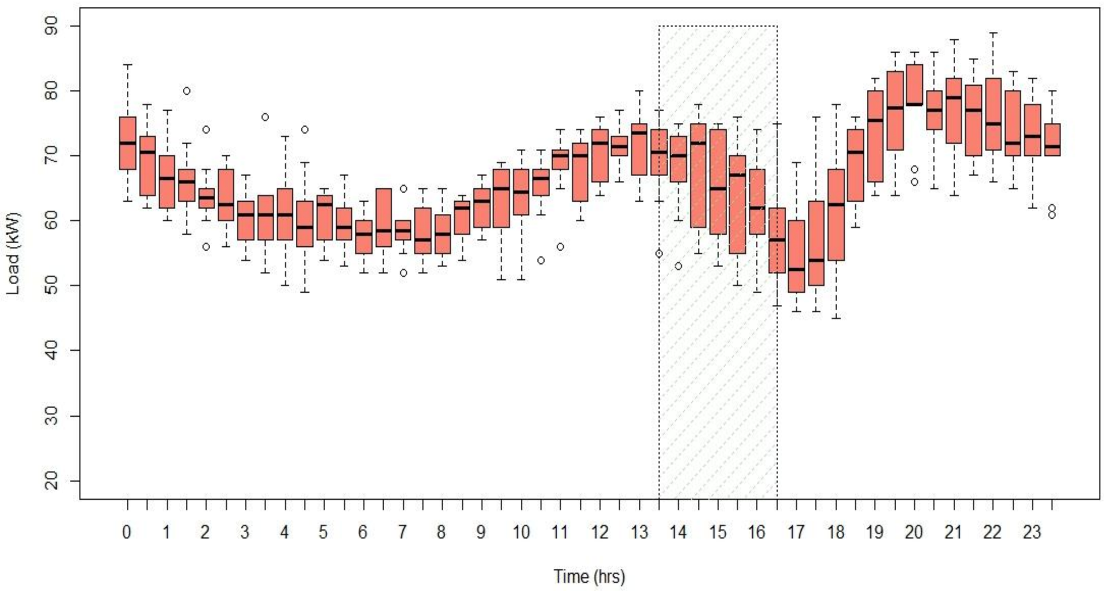


Figure 6.30: Boxplot for hourly load variation on Sundays, showing the time of PDR for CS2

Figure 6.31 shows the comparison of load for the CS2 DR day and the average for all Sundays. The load for CS2 was mostly below the Sunday average, however, when the PDR signal was sent, the load dropped from approximately 60kW to 55kW. The load continued to gradually decrease, even after the ND signal was sent at 4.30 p.m. After 6.00 p.m., when people started to switch on lights with their evening activities, the load increased to mimic its normal pattern.

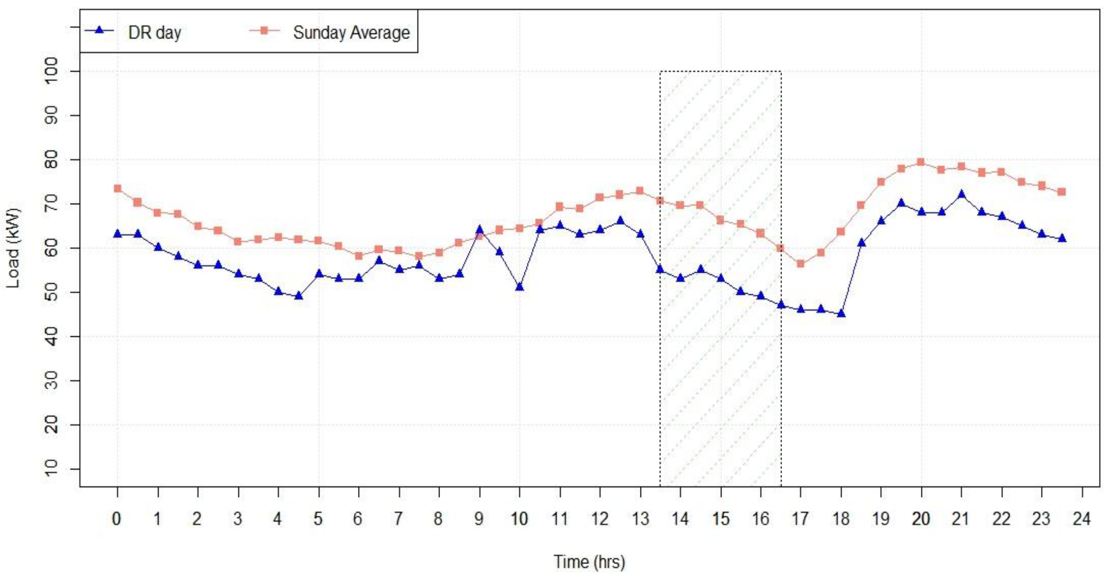


Figure 6.31: Load curves for CS2 and average for Sundays

The load variation trend in Figure 6.30 was also modeled using **Eq. 23**, to statistically evaluate the difference in load variation during the time of PDR. The values of the dummy variables in CS2 are the same as in CS1. *DSCD(t)* remains as '0' but the value of *DMCD(t)* is '1' during the PDR period, and the coefficient c_1 is the statistical difference in load achieved due to the DR from the participants. Table 6.8 presents the estimation results for CS2.

Table 6.8: Estimation results for the CS2 analysis

Coefficient	*Estimate value*	*Standard error*	*Significance**	*95% confidence interval*	
				Lower bound	*Upper bound*
a_0	66.2474	1.4113	0.0001	64.078	68.463
a_1	-4.6841	0.2959	0.0001	-5.257	-4.071
a_2	-3.1478	0.2975	0.0001	-3.712	-2.539
a_3	-2.0871	0.2948	0.0001	-2.667	-1.505
b_1	2.4896	0.2959	0.0001	1.904	3.082
b_2	4.5098	0.2934	0.0001	3.963	5.103
b_3	-3.0775	0.2948	0.0001	-3.642	-2.479
c_1	-5.5373	1.9297	0.0034	-9.498	-1.857

**the estimated value is significant at 95% if this value is less than 0.05*

The estimation of c_1 for the CS2 model shows that the load comparatively decreased by 5.54kW during the time when PDR was carried out.

6.4.3 Constraint scenario 3 (CS3)

The highlights of CS3 are outlined below:

- PDR was carried out on Friday, 05 October 2012.
- The scenario was the same as CS2, but it was carried out on a different day of the week.
- The PDR signal to conserve energy to MCD level was sent at 11.30 a.m.

- The ND consumption signal was sent at 5.00 p.m.

Figure 6.32 shows the boxplot for the hourly load of all Fridays logged during the period from August 2012 to October 2012. The shaded area in the figure represents the time when PDR was carried out for CS3.

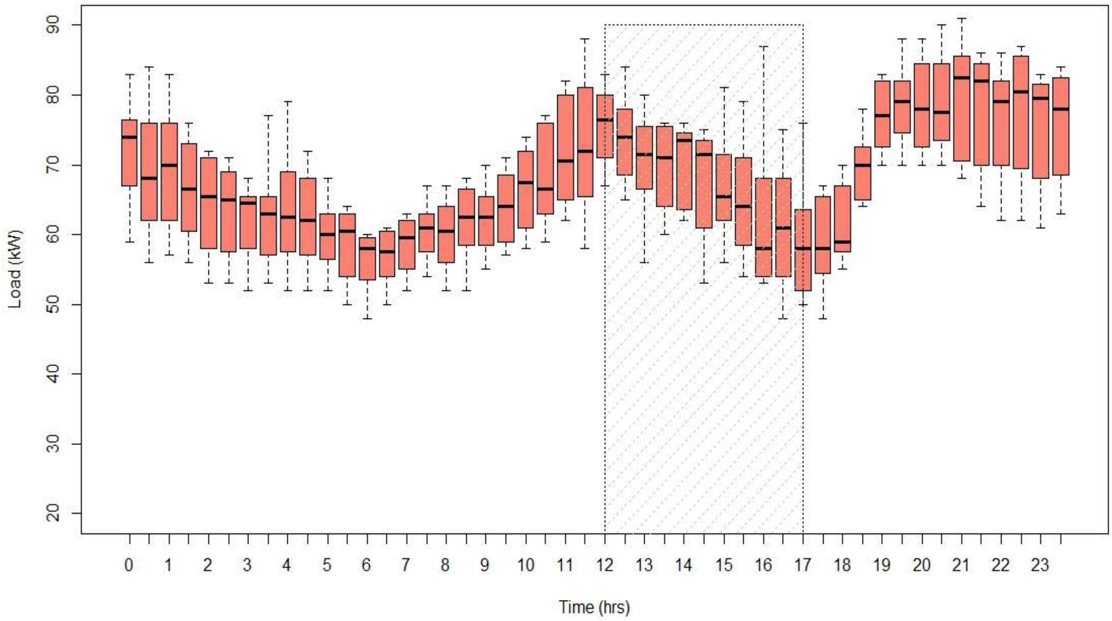


Figure 6.32: Boxplot for hourly load variation on Fridays, showing the time of PDR for CS3

Figure 6.33 shows the comparison of load for the CS3 DR day and the average for all Fridays. The load for the CS3 DR day was followed the average Friday load pattern until 8.00 a.m., after which the load started to rise. When the load peaked at approximately 11.30 a.m., the PDR signal was generated. From this time the measured load from the powerhouse dropped from approximately 90kW to 75kW at noon and then to a load of approximately 56kW at 5.00 p.m. Even though the ND consumption signal was sent at 5.00 p.m., the load decreased a further 2kW in the next hour and then increased to its normal evening pattern.

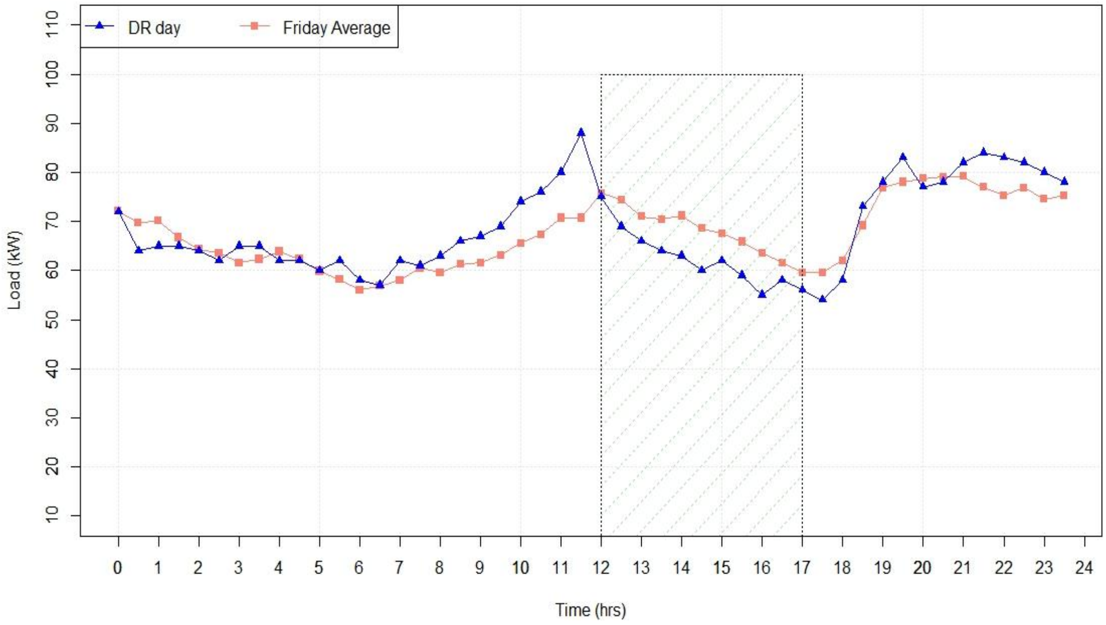


Figure 6.33: Load curves for CS3 and average for Fridays

Table 6.9 presents the estimation results for CS3 when the load variation was modeled using **Eq. 23**, to statistically analyze the difference in load variation due to PDR. Again, the CS3 case was for a MCD condition only, hence the value that shows the statistical difference is the coefficient c_1.

Table 06.9: Estimation results for the CS3 analysis

Coefficient	*Estimate value*	*Standard error*	*Significance**	*95% confidence interval*	
				Lower bound	*Upper bound*
a_0	67.7246	2.041	0.0001	65.077	70.465
a_1	-5.3533	0.3324	0.0001	-6.027	-4.688
a_2	-3.3682	0.3342	0.0001	-4.061	-2.724
a_3	-1.6645	0.3299	0.0001	-2.333	-1.02
b_1	1.9728	0.3353	0.0001	1.308	2.657
b_2	5.2862	0.3286	0.0001	4.63	5.938
b_3	-3.3987	0.3285	0.0001	-4.066	-2.743
c_1	-7.6575	1.6512	0.0001	-10.874	-4.4

**the estimated value is significant at 95% if this value is less than 0.05*

The estimation of c_1 for the CS3 model shows that the load comparatively decreased by 7.7kW during the time when PDR was carried out.

6.4.4 Constraint scenario 4 (CS4)

The highlights of CS4 are outlined below:

- PDR was carried out on Monday, 08 October 2012.
- The CS4 was a test for both MCD and SCD conditions.
- The scenario was that fuel delivery was delayed by a week due to bad weather, with possibility of being delayed further.
- Text PDR signal to conserve energy to MCD level was sent at 9.30 a.m. This was followed by the SCD level signal sent at 1.00 p.m.
- The ND consumption signal was sent at 4.00 p.m.

Figure 6.34 illustrates the boxplot for the hourly load of all Mondays logged during the period from August 2012 to October 2012. The shaded area represents the time when the PDR was carried out.

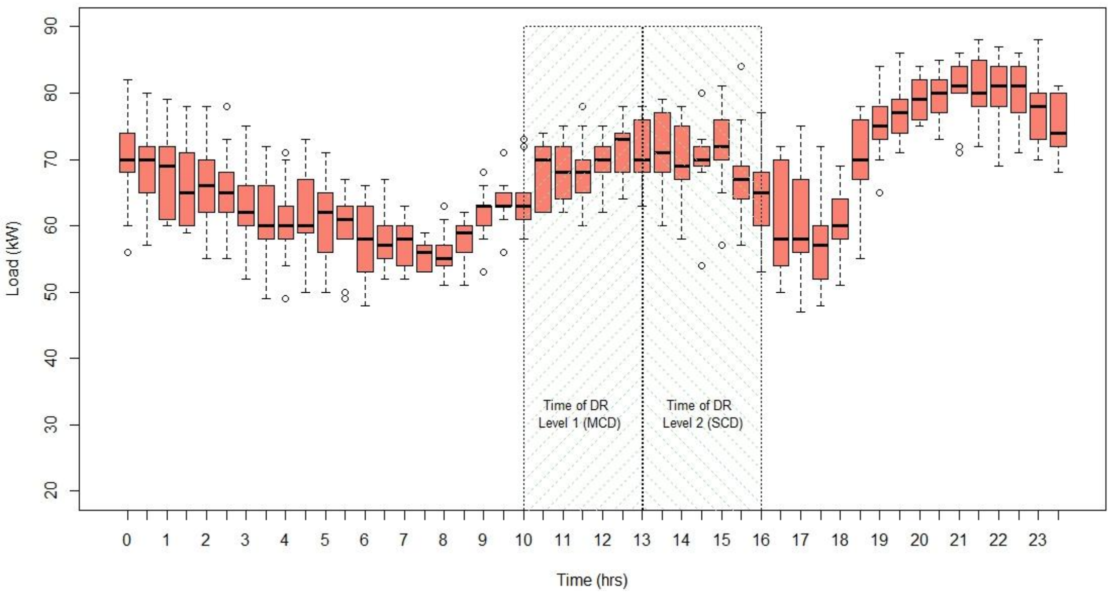


Figure 6.34: Boxplot for hourly load variation on Mondays, showing the time of PDR for CS4

Figure 6.35 shows the comparison of load for the day when CS4 was carried out and the average for all Mondays. The load for the CS4 DR day was initially a little higher than the average Monday load pattern until 8.00 a.m. At 9.30 a.m. the PDR signal for the MCD condition was sent. From this time, the measured load from the powerhouse shows that the load remained at the same level instead of following the average load pattern. This is the time when the load normally starts to rise and then peak at mid day. The second signal was sent at 1.00 p.m. asking to constraint use to the SCD level. Figure 6.35 illustrates that the CS4 DR day load dropped further from approximately 60kW at 1.00 p.m. to 55kW at 4.00 p.m. The ND signal was sent to the participants at 4.00 p.m. informing them to resume with normal consumption. Even though the ND consumption message was sent at 4.00 p.m., the load decreased a further 8kW over the next two hours, after which it started to increase to its normal evening pattern. However, this particular day, the usual evening peak did not occur. Instead the load remained at approximately 75kW after 7.00 p.m.

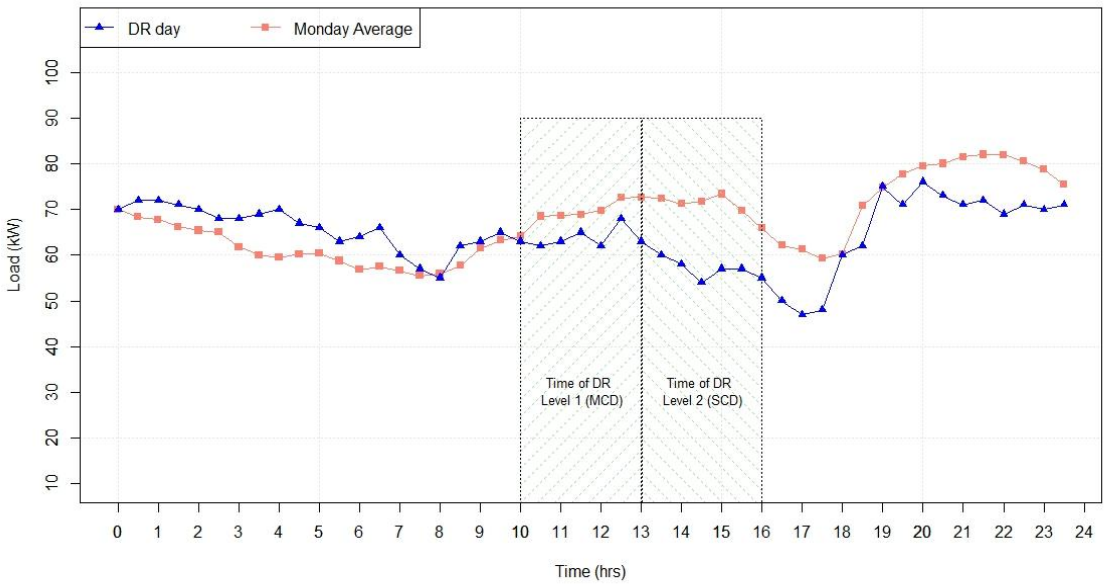


Figure 6.35: Load curves for CS4 and average for Mondays

The load variation for the CS4 DR day was also modeled by **Eq. 23**, to statistically evaluate the difference in load variation during the time of PDR. However, in this case, the two dummy variables were used for analysis. *DMCD(t)* is assigned a value

'1' during the period when the MCD was carried out and the variable *DSCD(t)* is assigned '1' during the time when the SCD was carried out. As a result, the coefficient c_1 is the statistical difference in load achieved for the MCD level and c_2 is the statistical difference in load achieved during the SCD level of DR from the participants. Table 6.10 presents the estimation results for CS4.

Table 06.10: Estimation results for the CS4 analysis

Coefficient	*Estimate value*	*Standard error*	*Significance**	*95% confidence interval*	
				Lower bound	*Upper bound*
a_0	67.451	1.1973	0.0001	65.124	69.546
a_1	-6.3344	0.3431	0.0001	-7.029	-5.668
a_2	-2.5686	0.3454	0.0001	-3.218	-1.874
a_3	-2.9414	0.3434	0.0001	-3.639	-2.297
b_1	2.8722	0.3519	0.0001	2.205	3.587
b_2	5.2591	0.346	0.0001	4.559	5.922
b_3	-2.9211	0.3444	0.0001	-3.593	-2.253
c_1	-5.4086	2.1615	0.012	-9.845	-1.162
c_2	-10.6584	2.2983	0.0001	-15.259	-6.237

**the estimated value is significant at 95% if this value is less than 0.05*

The estimation results show that during the time of MCD, the load comparatively decreased by approximately 5.5kW (c_1), and during the time of SCD, it decreased by approximately 11kW (c_2).

6.4.5 Constraint scenario 5 (CS5)

The highlights of CS5 are outlined below:

- PDR was carried out on Friday, 12 October 2012.
- The fuel delivery scenario was the same as in CS2, except CS5 was a test for the response during the evening peak time.
- The PDR signal to conserve energy to MCD level was sent at 6.30 p.m.

- The ND consumption signal was sent at 9.00 p.m.

Figure 6.36 shows the boxplot for the hourly load of all Fridays logged during the period from August 2012 to October 2012, and the shaded area represents the time when PDR was carried out.

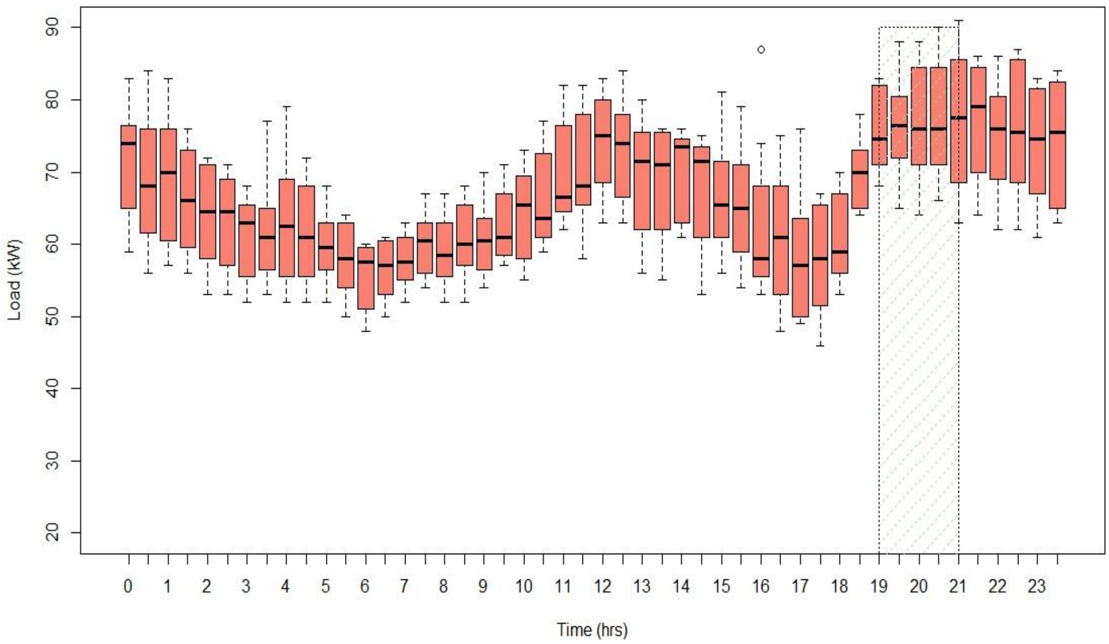


Figure 6.36: Boxplot for hourly load variation on Fridays, showing the time of PDR for CS5

Figure 6.37 shows the comparison of load for the CS5 DR day and the average for all Fridays. The load for the CS5 DR day was below the average Friday load pattern until 6.00 p.m., after which the load started to rise to the normal evening pattern. When the load reached approximately 75kW at 6.30 p.m., the PDR signal was generated. From this time the measured load from the powerhouse dropped to 68kW at 7.00 p.m. and then remained between 63kW and 68kW until the normal consumption message was sent at 9.00 p.m. Once the ND signal was sent, the load once again increased to the normal evening consumption pattern.

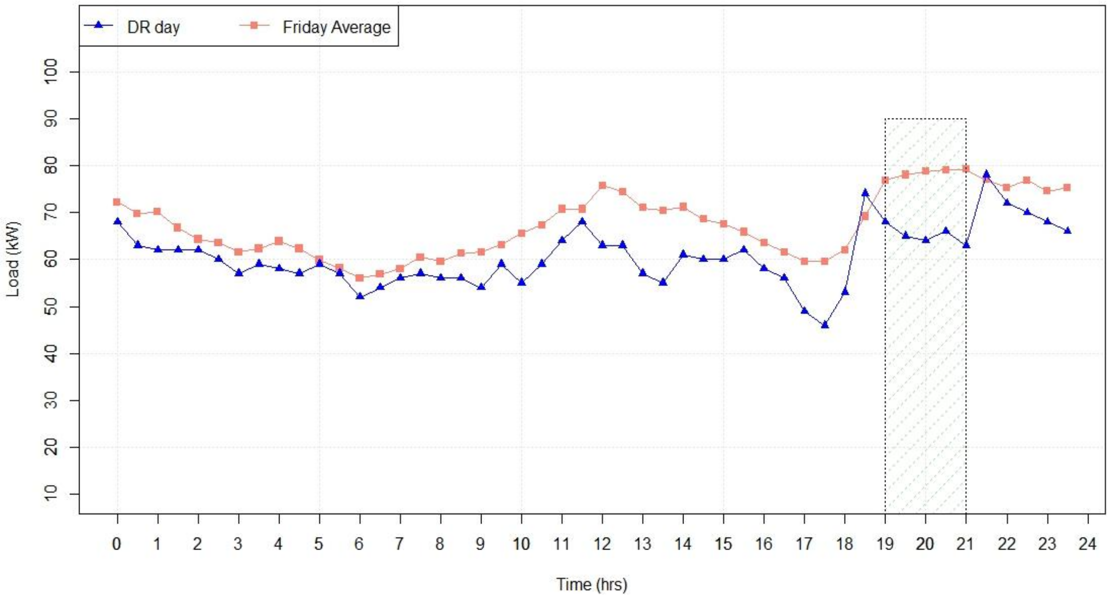


Figure 6.37: Load curves for CS5 and average for Fridays

Table 6.11 presents the results for CS5 when the load variation was modeled using **Eq. 23** to statistically analyze the difference in load variation due to PDR. Again, the CS5 case was for a MCD condition only, so the value showing the statistical difference is the coefficient c_1.

Table 06.11: Estimation results for the CS5 analysis

Coefficient	*Estimate value*	*Standard error*	*Significance**	*95% confidence interval*	
				Lower bound	*Upper bound*
a_0	66.6398	2.1674	0.0001	63.872	69.3687
a_1	-5.1868	0.3338	0.0001	-5.844	-4.514
a_2	-3.0734	0.3334	0.0001	-3.753	-2.4208
a_3	-1.6345	0.33	0.0001	-2.272	-0.967
b_1	2.4669	0.3313	0.0001	1.798	3.1215
b_2	4.8652	0.3312	0.0001	4.222	5.5275
b_3	-3.1801	0.3338	0.0001	-3.869	-2.5373
c_1	-4.5342	2.2446	0.042	-9.253	-0.2626

**the estimated value is significant at 95% if this value is less than 0.05*

Table 6.11 shows that during the time of the evening peak load, when the participants were asked to curtail their loads to the MCD level, the load decreased by approximately 4.5kW (c_1).

6.5 Fuel consumption comparison

The change in demand results in changes in the amount of fuel being consumed by the generator. Tables 6.12−6.15 present the fuel consumption and load details for the days when PDR were carried out, as well as the details for the same weekday for the period from August 2012 to October 2012.

Table 06.12: Fuel consumption and load details for CS1 (15 September 2012)

Day	*Fuel consumed (litres)*	*Units generated (kWh)*	*Average load (kW)*	*Maximum demand (kW)*	*Average fuel consumption rate (litres/kWh)*
20-Oct-12	1024	1435	60	75	0.71
13-Oct-12	1193	1559	65	89	0.77
6-Oct-12	1102	1607	67	88	0.69
29-Sep-12	1086	1607	67	84	0.68
22-Sep-12	1118	1387	58	76	0.81
15-Sep-12	**1118**	**1632**	**68**	**89**	**0.69**
1-Sep-12	1270	1733	72	93	0.73
25-Aug-12	1125	1526	64	87	0.74
18-Aug-12	1240	1717	72	94	0.72
11-Aug-12	1180	1650	69	85	0.72

Eq. 24 was used to calculate the reduction in the average consumption rate (RACR) due to PDR on a particular day.

$$RACR = \left(\frac{Mean\ value - Average\ of\ DR\ day}{Mean\ value}\right) \times 100 \qquad \textbf{Eq. 24}$$

where *RACR* is the reduction in average consumption rate (%), *'Mean value'* is the mean fuel consumption rate for all the compared days excluding the day when PDR was conducted (litres/kWh) and *'Average of DR day'* is the average fuel consumed on the day of PDR (litres/kWh).

From Table 6.12, the average fuel consumption rate for the DR day was 0.69liters/kWh. The mean for the rest of the days was 0.73liters/kWh. Therefore, the percentage reduction in the average fuel consumption rate for the CS1 DR day calculated using **Eq. 24** is: $\boldsymbol{RACR = 5.9\%}$

Table 06.13: Fuel consumption and load details for CS2 (23 September 2012)

Day	*Fuel consumed (liters)*	*Units generated (kWh)*	*Average load (kW)*	*Maximum demand (kW)*	*Average fuel consumption rate (liters/kWh)*
21-Oct-12	1118	1538	64	78	0.73
14-Oct-12	1151	1606	67	83	0.72
7-Oct-12	1183	1666	69	85	0.71
30-Sep-12	1118	1620	67	79	0.69
23-Sep-12	**985**	**1393**	**58**	**72**	**0.71**
16-Sep-12	1118	1591	66	80	0.7
2-Sep-12	1010	1425	59	68	0.71
26-Aug-12	1235	1653	69	86	0.75
12-Aug-12	1230	1632	68	82	0.75
5-Aug-12	1315	1760	73	89	0.75

From Table 6.13, the average fuel consumption rate for the CS2 DR day was 0.71liters/kWh. The mean for the rest of the days was 0.72liters/kWh. Therefore, the percentage reduction in the average fuel consumption rate for the CS2 DR day calculated using **Eq. 24** is: $\boldsymbol{RACR = 1.4\%}$

Table 06.14: Fuel consumption and load details for CS3 (05 October 2012) and CS5 (12 October 2012)

Day	*Fuel consumed (liters)*	*Units generated (kWh)*	*Average load (kW)*	*Maximum demand (kW)*	*Average fuel consumption rate (liters/kWh)*
19-Oct-12	1118	1402	58	76	0.8
12-Oct-12	**1017**	**1456**	**61**	**78**	**0.69**
5-Oct-12	**1094**	**1633**	**68**	**88**	**0.67**
28-Sep-12	1161	1613	67	84	0.72

21-Sep-12	1118	1449	60	75	0.77
31-Aug-12	1250	1725	72	88	0.72
24-Aug-12	1195	1606	67	83	0.74
10-Aug-12	1310	1783	74	91	0.73
3-Aug-12	1300	1751	73	87	0.74

Table 6.14 presents the results for both CS3 and CS5 DR days. The mean fuel consumption rate for all days, excluding the DR days was 0.75litres/kWh. Therefore, the percentage reduction in the average fuel consumption rate for the CS3 DR day is calculated as: $\boldsymbol{RACR = 10.7}\%$. The percentage reduction in the average fuel consumption rate for the CS5 DR day is calculated as: $\boldsymbol{RACR = 8}\%$

Table 06.15: Fuel consumption and load details for CS4 (08 October 2012)

Day	*Fuel consumed (liters)*	*Units generated (kWh)*	*Average load (kW)*	*Maximum demand (kW)*	*Average fuel consumption rate (liters/kWh)*
15-Oct-12	1140	1620	67	84	0.7
8-Oct-12	**1038**	**1546**	**64**	**76**	**0.67**
1-Oct-12	1140	1601	67	84	0.71
24-Sep-12	1118	1485	62	78	0.75
17-Sep-12	1151	1627	68	85	0.71
3-Sep-12	1145	1531	64	85	0.75
27-Aug-12	1225	1640	68	86	0.75
13-Aug-12	1255	1685	70	88	0.74
6-Aug-12	1303	1786	74	88	0.73

Table 6.15 presents the results for the CS4 DR day. The mean fuel consumption rate for all days, excluding the DR day was 0.73litres/kWh. Therefore, the percentage reduction in average fuel consumption rate for the CS4 DR day is calculated as: $\boldsymbol{RACR = 8.2}\%$

The fuel consumption details in Tables 6.12−6.15, show that except for the CS2 DR day, there was a reduction in fuel that was consumed when the DR day was compared to the same 'week-day'. However, there was a positive value for the percentage reduction in average fuel consumption rate on all the days when PDR was conducted.

Table 6.16 presents a summary of all the constraint scenarios, giving the generated signal level (or strength), the measure of response received by the participants and the RACR for each of the scenarios.

Table 06.16: Summary of all the constraint scenario results

Constraint scenario	*Signal strength*	*Response measure (kW)*	*RACR (%)*
CS1 (MCL)	Emergency	5.03	5.9
CS2 (MCL)	Conserve energy	5.54	1.4
CS3 (MCL)	Conserve energy	7.7	10.7
CS4 (MCL)	Conserve energy	5.4	8.2
CS4 (SCL)	Further reduction	10.7	
CS5 (MCL)	Conserve energy	4.5	8

6.6 Operator survey analysis and OCS validation

6.6.1 Powerhouse operators

The Fenfushi powerhouse employed six staff, all of them Male, to manage daily operation and maintenance. The average age of the employees was 22.4 years, with the youngest being 20 years and the oldest 25 years. Except for two employees, who had been employed for three years, the others had been employed for less than six months. The new employees had joined the team when the government took over the operation of the powerhouse in late February of 2012. The team leader had an employment history of three years and was officially trained in the field. However, the rest of the team had no official training in the field of work. Most of them were trainees, learning by experience.

6.6.2 Managing powerhouse duties

When the employees were asked about general information on the power generation facilities, everyone was aware of normal routine administrative details. For example, all were aware that there were three generators in working condition, the records were managed in a log book, and they all know details of the fuel storage tank.

The most interesting observation made during the survey was that the generators were switched on a routine basis. Gen Set 3 was always switched on at 3.00 a.m. and ran until 10.00 a.m. From this time, the higher rated generator took over. The switch over did not have any relation to the load on the system. The only time when this routine was changed was if the smaller generator gets overloaded during its designated period, or if any of the generators were malfunctioning. When the employees were asked about why this was done, their reply was:

> *"...normally from 3.00 a.m. until 10.00 a.m. the load is very low and that's why the smallest generator is on load at that time. After 10.00 a.m. the load begins to rise, therefore, we keep the bigger generator on load for that time."*

The staff were just carrying out their duties as they were told by their senior. This is a clear indication of the level of training that had been given to the powerhouse operating staff.

6.6.3 OCS validation

The staff were given the opportunity to use the UFCOCS program and familiarize themselves with its functions. Feedback received from the staff regarding the program was very positive. Everyone said they were able to understand how the program worked and found the program to be interactive enough. The survey results also showed that the powerhouse employees thought that UFCOCS would help them to manage record keeping better and would highly recommend such a program to be used in the powerhouse. The staff also suggested that the program could help them in managing periods when there were constraints in fuel use or power generation shortages.

6.6.4 Validation of the method used for load forecasting

The PDR methodology was simulated using a program written in MATLAB®, to test the use of the DUF matrix in demand forecasting (refer **section 4.5.2)**. For simulation purposes, a real-time load was generated on an hourly basis, by using random values that is closer to the level of constraint that was in effect. The program also tested if the fuel could be managed by the proposed method, in the event of a constraint in fuel supply.

Simulations were carried out to meet different levels of constrained conditions. Table 6.17 summarizes the results of four such simulations. In Simulations 1−3, the amount of fuel received is constrained and therefore, different levels of PDR are required from the customers. Simulation 4 is the "normal" fuel arrival routine for the island of Fenfushi and it does not require any PDR.

Table 06.17: Summary of Matlab simulation results

Simulation run	***Amount of fuel received (litres)***	***Time between fuel shipments (days)***	***Total time spent***					
			Forecast			***Real-time***		
			ND	***MCD***	***SCD***	***ND***	***MCD***	***SCD***
Simulation 1	10,000	20	14 Days 16 Hours	1 Day 8 Hours	4 Days	14 Days 14 Hours	1 Day 9 Hours	4 Days 1 hour
Simulation 2	8,000	15	12 Days 22 Hours	14 Hours	1 Day 12 Hours	12 Days 23 Hours	13 Hours	1 Day 12 Hours
Simulation 3	9,000	18	13 Days 17 Hours	1 Day 2 Hours	3 Days 5 Hours	13 Days 16 Hours	1 Day 2 Hours	3 Days 6 Hours
Simulation 4	10,000	15	15 days	0	0	15	0	0

The load variation for 'Simulation 1' is presented in Figure 6.38. The figure shows that DR is requested from the customers on five occasions. The forecasted load gives a very close approximation of how the randomly generated real-time load varies, and this is confirmed by the results in Table 6.17.

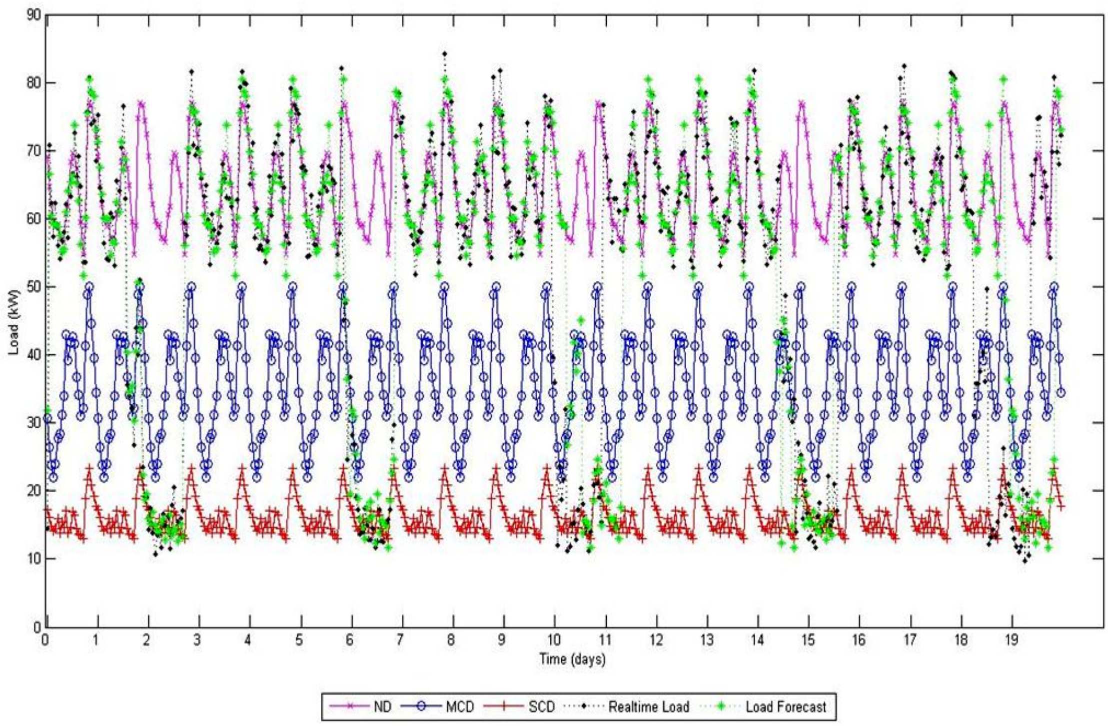


Figure 6.38: Load variation graph for 'Simulation 3'

The code written using the MATLAB® program to carry out the simulations is presented in Appendix A8.

6.7 Summary

This chapter has presented the analysis and the results of the PDR system with the help of the case study carried out on Fenfushi. Among the surveyed population, the majority (40%) of the people were living in houses built between 1991−2000. Most of the families on Fenfushi choose to live as an extended family in the same household, consequently increasing the number of bedrooms in a dwelling. This leads to Fenfushi having a higher average household occupancy rate (11.7) than that of the atoll (6.1) that it belongs to. Of the households, 93% had access to an open well that could be used during electrical energy constraints. The average monthly electricity bill for a household was NZD$109.69 with a standard deviation of NZD$59.5. The daily load curve for the months from March 2012 to October 2012 show that the island load varied between 40kW and 90kW, with peaks at mid-day and dinner time.

The key results of the audit survey are summarized as follows:

- Every household had at least one of each of the following electrical appliances: fan, light, electric iron and washing machine.
- Approximately 97% of households had at least one fridge/freezer
- 93% of households had TVs and electric water pumps
- 77% of households were equipped with electric insect repellents
- 47% of households had at least one air conditioner

In this chapter, the energy audit and survey results were presented and analyzed. Responses to survey questions regarding customer concerns about price, environmental effects and the security of the power system were outlined. Responses to the adaptability survey were discussed, and the different categories of essentiality for household end-use appliances were identified and classified. Customer responses regarding their expected level of participation during energy-constrained situations were presented. The hourly variation factors for the commonly utilized appliance categories were calculated and presented, along with the three reference load curves for Fenfushi island.

A detailed statistical analysis of the constrained scenarios practiced during the case study was presented in **section 6.4**. All five different scenarios have showed a statistically significant reduction in energy use during the period when participatory demand response (PDR) was requested from the customers. The reductions during the MCD condition varied from a minimum of 4.5kW to a maximum of 7.7kW, while a reduction of 10.7kW was achieved during the SCD condition.

This chapter also presented a comparison of fuel consumption between the DR days and the same week-days in the period from August 2012 to October 2012. The chapter also presented the analysis of the powerhouse operator survey results and their response to the UFCOCS program that was developed by the author.

The results for the simulations completed to test the validity of the demand forecast method introduced by this thesis, using the demand use factor (DUF) matrix, were also presented in this chapter. The results showed a very close approximation between the forecasted load and the real-time load. As a consequence, this method can be utilized in the utility industry to get an approximation for the hour-ahead demand forecast, and so assist them into preparing for DR signalling.

CHAPTER 7

CONCLUSION, RECOMMENDATIONS AND FUTURE WORK

THROUGHOUT the PhD research program presented in this thesis, a novel real-time feedback control method for a resource constrained power grid using participatory demand response (PDR) was developed and evaluated. The motivation for carrying out this research and the objectives were outlined in Chapter 1. A literature review of the published work was then presented in Chapter 2 in order to establish the contributions this research program offers to the body of knowledge. The main contribution of this thesis is the novel theory Participatory Demand Response (PDR), which was discussed in Chapter 3. Chapter 4 provided a detailed description of how the PDR model could be implemented into a remote mini-grid. The concept validation procedure was explained in Chapter 5, and Chapter 6 presented the analysis and the results for the case study tests carried out on the island of Fenfushi in the Maldives.

This chapter summarizes the main findings observed in the past chapters, and provide the conclusions and recommendations for future work, including possible research directions for future researchers.

7.1 Conclusions

People living on islands or in other remote areas rely primarily on power system technology utilizing stand-alone diesel generators. A major issue for remote communities is the cost and lack of reliability of diesel oil supplies for power generation. Power generation in these areas can easily be disrupted by problems with the transportation of diesel or rises in fuel price, which limits shipment quantity. Customers in remote areas experience power outages often, but find them just as disruptive as people connected to national power grids. Additional renewable generation, battery storage, synchronous operation and optimal design of the diesel power plant could help to avoid power outages when fuel supplies are disrupted. Establishing such a system requires a huge initial investment. However, the economies of remote communities are often based things such as tourism, traditional agriculture and fishing or crafts, all of which produce limited surplus income. Therefore, financial support from government and profit-making private agencies that operate in the remote area is needed for development and maintenance of village-scale electricity supply systems.

A critical review of literature on remote area power supply (RAPS) systems and the different control strategies currently used for managing energy demand in these systems was presented in Chapter 2. The literature has shown that the most feasible method for power supply in remote areas is to install hybrid systems. However, most of these remote electrical power grids are set up as open flow systems. Hence, power availability scheduling and 'rolling blackouts' have been used by some communities as control strategies to manage the supply side complications. Instead of approaching the utility constraints from the supply side, current practices include demand side approaches to manage the electricity grid and power generation constraints. This requires designing and implementing a feedback controlled energy system. Different motivating factors have been used by power suppliers to achieve demand response during peak load periods. The power suppliers provide information to customers regarding how end-use behavior impacts factors such as carbon emissions, price and security of supply. What is missing from the literature on feedback control systems used in power generation is a link between the fuel availability and the system directives as explained in **section 1.1**. The controller has no feedback signal to activate the customers during a fuel availability constraint. This thesis presented a new DSM technique that can be used in remote power grids to manage the community demand by eliciting voluntary participation from end-users during resource constrained situations.

The feedback controlled PDR model developed in this thesis adopts Krumdieck's regional energy system model to describe its control system. Knowledge, reason and education of the customers are the three main reference elements that govern the PDR system and these elements were explained in **section 3.5**. The design of the PDR model was illustrated and explained in Chapter 3. The implementation procedure for the PDR design on a mini-grid was discussed in Chapter 4. This procedure was divided into four main steps for ease of implementation. Step one was the characterization of end-use loads based on the level of essentiality to the customer. The second step was to gather utility records and, calculate the HVF and appliance saturation rate. Designing a fuel consumption control strategy and building the reference load curves was the third step, while the final step was to create the design of the operator control system. The author designed an operator control system for the case study conducted on the island of Fenfushi, and this system was explained in **sections 4.5** and **4.6**.

Chapter 5 provided a detailed explanation of the electrical power generation and distribution, fuel supply and fuel storage systems that existed on Fenfushi. The island had used a flat rate of approximately US$0.4 per kWh as a tariff structure until February 2012. The current tariff is based on a bandwidth charge structure, and this was presented in Table 5.2. Testing the PDR control design involved validating two concepts. These were the customer side PDR control system and the operator side control system. The validation procedure was explained in Chapter 5.

Chapter 6 presented the results and a thorough analysis of the case study on Fenfushi. The demographic analysis of the island showed that the people of Fenfushi prefer to live as an extended family, sharing the same dwelling but separated by private bedrooms. As a consequence, the household occupancy rate on Fenfushi was 11.7 while the atoll's rate was 6.1. As much as 93% of the households had access to an open well that could be used during periods of electrical energy constraints. The daily load curve for the period from March 2012 to October 2012 showed that the island load varied between 40kW and 90kW, with a mid-day and a dinner time peak. The audit survey showed that all houses were equipped with electric fans, lights, electric irons and washing machines. Of all the households, 97% had at least one fridge/freezer, and 93% owned TVs and electric water pumps. 77% were equipped with electric insect repellents and almost half of the population (47%) own at least one air conditioner.

Using the responses to the adaptability survey, the household end-use appliances in Fenfushi were classified into three different categories of essentiality. The author calculated and presented the hourly variation factors (HVFs) for the commonly utilized appliance categories for Fenfushi island, as there was no available data of this nature for remote communities such as the Maldivian islands. Using the HVF data, adaptability survey details and the reference load equations, the ND, MCD and SCD curves for Fenfushi were calculated and illustrated in Figure 6.27.

When the survey was being carried out, some interesting behavior patterns were observed amongst the community. The survey was being conducted for a randomly chosen sample of the island population, however, the discussions held for the participating population was spread to the entire community the same day. People who were not within the randomly chosen group approached the author to discuss the situation of the electrical energy supply in the island. People started talking about their consumption issues with much interest. This behavior indicated a potential interest in participation among the entire population of the island in regards to the energy related issues. The results of the statistical analysis of the energy constrained scenarios practiced on the island showed the level of participation achieved from the island population.

The statistical analysis of the constrained scenarios (CS1−CS5) were presented in **section 6.4**. A significant reduction in energy use was achieved during all five scenarios. Constrained scenario 1 (CS1) was an actual emergency situation that developed on the island on 15 September 2012, while the remaining scenarios (CS2−CS5) were created by the author. The customer response and load reduction achieved during CS1 was very impressive. Even though the level of participation requested from the customers was for a MCD condition, there was a notable drop in load when compared to the average load for the same 'week-day'. The key to such a drop may be in the signal sent to the participants. The text message sent to the participating customers' mobile phones included the word "***Emergency***", when explaining the powerhouse situation. People have the tendency to physically attend the site and identify what is happening when such information is provided to them. As a consequence, a high level of participation was achieved even though the participation level asked was for a MCD. The overall results from the five scenarios showed that for the MCD condition reductions in load varied between a minimum of 4.5kW to a maximum of 7.7kW. Results indicated a reduction of 10.7kW was achieved from the participants during the SCD condition.

The fuel consumption comparison for the five DR days shown in Tables 6.12-6.16 showed a positive reduction on the days when PDR was conducted. This could be improved by using a properly organized power generation schedule. The author observed that the generator schedule was preset and did not depend on variations in the island load. Up until 15 September 2012, the lowest rated operational generator at 80kW (Gen Set 3) ran from 2:30 a.m. to 10:30 a.m., then during the next shift Gen set 1 (128kW) operated. After installing the 160kW generator, Gen Set 2, on 15 September 2012, the only change made to the generator schedule was to swap Gen Set 1 (128kW) with Gen Set 2 (160kW). The current generator schedule runs Gen Set 3 (80kW) for the first shift and Gen Set 2 (160kW) for the second shift.

The demand forecast simulations carried out using DUF matrices showed a close approximation between the forecasted load and the real-time load. Therefore, the method for demand forecasting presented by the thesis can be used by the powerhouse operators to predict the hour-ahead load. This method can assist those using the PDR system to keep stakeholders prepared for any constraints that the community may confront.

The thesis has introduced PDR as a strategy to manage the end-user demand in order to maintain a sustainable and secure power supply in remote energy constrained electrical power grids. The PDR strategy was designed as a feedback control system that utilizes control of choices about activities and appliance use to manage the demand to match fuel supply margin. In remote power grids where the power generation requires diesel fuel to be transported on a regular basis, PDR can be utilized to maintain a constant supply of power during situations where there are constraints in the availability of fuel. The objective of the PDR strategy is to manage the amount of energy being consumed depending on how much fuel is available, such that continuous access to electricity can be generated to satisfy at least the most essential loads for consumers. Long term lower energy pricing should also be a major benefit of integrating PDR into the power system. The only other alternatives are investing in other possibilities for renewable energy generation and storage, larger fuel bunkers, or using less fuel when it is most expensive during a fuel price spike. Consumers have to be well informed about the benefits and most importantly, about the electrical appliances being used in the household in order to achieve the best results. The case study presented a successful application of the PDR design in a remote community and the results conclude that the design can be used to manage a resource constrained electrical energy power grid by integrating community participation.

7.2 Limitations in the case study

There were a few limitations in the Fenfushi case study. The main limitations are listed below.

- The energy audit was carried out for the residential households only, while the entire community load consisted of governmental and commercial loads. However, in remote communities, governmental and commercial loads are very low in comparison to the residential loads. Therefore, in this analysis these loads were assumed to be negligible.

- The demand response analysis used the load data collected from the powerhouse. This data is the load for the entire island community. Due to financial and technical limitations, the author was not able to monitor the responses from the individual participating households. However, by statistically analyzing the difference in the community load during the time when the demand response was carried out, a quantitative value for the response was achieved.

7.3 Recommendations

The following comments and recommendations could be useful for better operating and managing remote area power generation to provide efficient power supply to end-users in energy constrained situations. These recommendations apply for the immediate staff of powerhouse operations as well as for utility managers at the policy-making level.

Establishing coordination between the power supplier and the consumers is essential.

During CS1, the powerhouse staff learned that by informing the customers about power supplier side difficulties, and requesting customers to co-operate with them by reducing demand, load curtailment can be avoided. With this knowledge, the powerhouse staff carried out a similar request on another occasion when the generation situation was constrained and they were having difficulties keeping up with the demand. On a normal day, these situations lead the powerhouse staff to consider "rolling black-outs" in order to manage the system. Powerhouse staff informed the author that instead of curtailing the load, they attempted the PDR method, and this method helped them to reduce the load on the system to a stable level. This information indicates that "rolling black-outs" can be avoided if a good communication or coordination can be established between the stakeholders. Consumers need to be aware of the constraint situations to voluntarily participate in decreasing their consumption in order to avoid any power disruption.

The generator operation schedule should be based on the community load pattern.

Currently, the powerhouse runs on a preset generator operation schedule that has been prepared with very little consideration to the present load pattern. The staff are blindly following the schedule that was followed by their predecessors. The author observed that, due to this schedule, the highest rated generator was being run when the community load was very low. This is very inefficient when fuel consumption is in consideration. The general load pattern of the community needs to be utilized to prepare an efficient schedule for running the generators. This simple change can minimize a good amount of unnecessary fuel consumption and hence increase the efficiency of power generation.

Sufficient knowledge and training should be provided to the staff at the powerhouse.

The utility mangers should ascertain that proper knowledge and training is provided to the staff operating the powerhouses at the policy level. On the island of Fenfushi, only one out of the six staff had basic training in the field, and only two of them had over three years of experience. The rest of the staff were just trainees learning by experience, and had only been on the job for less than six months. The author had observed that lack of knowledge and skill can lead to very irresponsible actions. During the field work period, the staff had stopped recording the hourly load data and when asked about it, the reason put forward was that they had run out of printed 'log sheets'. In order to print the log sheets the printer needed a cartridge, which was being shipped from the capital island and hadn't arrived yet. The staff did not have a proper understanding of the value of the data that was being lost. Otherwise, they could have attempted to record the data on plain paper. This situation undoubtedly indicates that staff with adequate knowledge and responsibility are required and regular, monitored training should be provided for smooth operation of the powerhouse.

7.4 Potential future work

This thesis has presented a design and evaluation of real-time feedback control of a resource constrained remote electric power grid using participatory demand response (PDR). The design was implemented on an island in the Maldives to validate the concepts and evaluate the possible outcomes. Potential areas of future work are identified below.

- During the case study conducted in this research, the signaling was carried out by sending messages to the mobile phones of the participating customers. Further research can be carried out on developing better Information and Communication Technology (ICT) solutions for this process such that the stake holders are better connected and informed.

- Even though this research involved the PDR design implementation on a remote community, this area of study has potential for research to identify how PDR can be implemented on more developed power grids. The design can be incorporated in to a smart grid to better manage the system.

- The UFCOCS was a program developed by the author to be used in the Fenfushi island case study. However, a more sophisticated program including multiple functions to manage a more complicated grid can be developed.

- The island of Fenfushi had a single source of energy for power generation. If the PDR design is utilized in a power grid that includes renewable energy sources, the resulting energy system could be a more sustainable solution for remote power systems.

REFERENCES

Aalami, H. A., Moghaddam, M. P., & Yousefi, G. R. (2010a). Modeling and prioritizing demand response programs in power markets. *Electric Power Systems Research, 80*(4), 426-435.

Aalami, H. A., Moghaddam, M. P., & Yousefi, G. R. (2010b). Demand response modeling considering Interruptible/Curtailable loads and capacity market programs. *Applied Energy, 87*(1), 243-250.

Affonso, C. M., & Silva, L. C. P. d. (2010). Potential benefits of implementing load management to improve power system security. *International Journal of Electrical Power & Energy Systems, 32*(6), 704-710.

Aghamohammadi, M. R., & Abdolahinia, H. (2014). A new approach for optimal sizing of battery energy storage system for primary frequency control of islanded Microgrid. *International Journal of Electrical Power & Energy Systems, 54*(0), 325-333. doi: http://dx.doi.org/10.1016/j.ijepes.2013.07.005

Ajzen, I. (1991). The theory of planned behavior. *Organizational Behavior and Human Decision Processes, 50*(2), 179-211. doi: Doi: 10.1016/0749-5978(91)90020-t

Ajzen, I., & Madden, T. J. (1986). Prediction of goal-directed behavior: Attitudes, intentions, and perceived behavioral control. *Journal of Experimental Social Psychology, 22*(5), 453-474. doi: Doi: 10.1016/0022-1031(86)90045-4

Alagoz, B. B., Kaygusuz, A., & Karabiber, A. (2012). A user-mode distributed energy management architecture for smart grid applications. *Energy, 44*(1), 167-177. doi: http://dx.doi.org/10.1016/j.energy.2012.06.051

Alajmi, A. (2012). Energy audit of an educational building in a hot summer climate. *Energy and Buildings, 47*(0), 122-130. doi: http://dx.doi.org/10.1016/j.enbuild.2011.11.033

Albadi, M. H., & El-Saadany, E. F. (2008). A summary of demand response in electricity markets. *Electric Power Systems Research, 78*(11), 1989-1996.

Ali Nandar, C. S. (2013). Robust PI control of smart controllable load for frequency stabilization of microgrid power system. *Renewable energy, 56*(0), 16-23. doi: http://dx.doi.org/10.1016/j.renene.2012.10.032

Ambia, M. N., Islam, M. K., Shoeb, M. A., Maruf, M. N. I., & Mohsin, A. S. M. (2010). *An analysis & design on micro generation of a domestic solar-wind hybrid energy system for rural & remote areas - perspective Bangladesh.* Paper presented at the Mechanical and Electronics Engineering (ICMEE), 2010 2nd International Conference on.

Anderson, W., & White, V. (2009). Exploring consumer preferences for home energy display functionality. *Centre for Sustainable Energy, Tech. Rep*.

Ashok, S. (2007). Optimised model for community-based hybrid energy system. *Renewable energy, 32*(7), 1155-1164.

Avci, M., Erkoc, M., Rahmani, A., & Asfour, S. (2013). Model predictive HVAC load control in buildings using real-time electricity pricing. *Energy and Buildings, 60*(0), 199-209. doi: http://dx.doi.org/10.1016/j.enbuild.2013.01.008

Ayres, R. U. (2008). Sustainability economics: Where do we stand? *Ecological Economics, 67*(2), 281-310. doi: http://dx.doi.org/10.1016/j.ecolecon.2007.12.009

Bamberg, S., Hunecke, M., & Blöbaum, A. (2007). Social context, personal norms and the use of public transportation: Two field studies. *Journal of Environmental Psychology, 27*(3), 190-203. doi: DOI: 10.1016/j.jenvp.2007.04.001

Belmili, H., Haddadi, M., Bacha, S., Almi, M. F., & Bendib, B. (2014). Sizing stand-alone photovoltaic–wind hybrid system: Techno-economic analysis and optimization. *Renewable and Sustainable Energy Reviews, 30*(0), 821-832. doi: http://dx.doi.org/10.1016/j.rser.2013.11.011

Berry, A., Platt, G., & Cornforth, D. (2010, 21-24 June 2010). *Minigrids: Analysing the state-of-play*. Paper presented at the Power Electronics Conference (IPEC), 2010 International.

Billinton, R., & Satish, J. (1996). Effect of rotational load shedding on overall power system adequacy indices. *Generation, Transmission and Distribution, IEE Proceedings-, 143*(2), 181-187. doi: 10.1049/ip-gtd:19960051

Bock, M. J. (1998). *An analysis of the factors influencing demand-side management activity in the electric utility industry*. Ph.D., State University of New York, Binghamton.

Böhringer, C., & Rutherford, T. F. (2009). Integrated assessment of energy policies: Decomposing top-down and bottom-up. *Journal of Economic Dynamics and Control, 33*(9), 1648-1661. doi: DOI: 10.1016/j.jedc.2008.12.007

Bompard, E., Huang, T., Wu, Y., & Cremenescu, M. (2013). Classification and trend analysis of threats origins to the security of power systems. *International Journal of Electrical Power & Energy Systems, 50*(0), 50-64. doi: http://dx.doi.org/10.1016/j.ijepes.2013.02.008

Branker, K., Pathak, M. J. M., & Pearce, J. M. (2011). A review of solar photovoltaic levelized cost of electricity. *Renewable and Sustainable Energy Reviews, 15*(9), 4470-4482. doi: http://dx.doi.org/10.1016/j.rser.2011.07.104

Breyer, C., Gerlach, A., Schafer, D., & Schmid, J. (2010, 18-22 Dec. 2010). *Fuel-parity: New very large and sustainable market segments for PV systems*. Paper presented at the Energy Conference and Exhibition (EnergyCon), 2010 IEEE

International.

Brown, H. E., Suryanarayanan, S., & Heydt, G. T. (2010). Some Characteristics of Emerging Distribution Systems Considering the Smart Grid Initiative. *The Electricity Journal, 23*(5), 64-75. doi: http://dx.doi.org/10.1016/j.tej.2010.05.005

Burgess, J., & Nye, M. (2008). Re-materialising energy use through transparent monitoring systems. *Energy Policy, 36*(12), 4454-4459. doi: http://dx.doi.org/10.1016/j.enpol.2008.09.039

Camerlynck, J. (2004). Modelling of renewable energy systems in the Maldives (D. o. S. T. a. Society, Trans.): Utrecht University.

Capasso, A., Grattieri, W., Lamedica, R., & Prudenzi, A. (1994). A bottom-up approach to residential load modeling. *Power Systems, IEEE Transactions on, 9*(2), 957-964. doi: 10.1109/59.317650

Capeheart, B., & Spiller, M. (2004). Chapter 3 Energy Auditing. In S. Doty & W. C. Turner (Eds.), *Energy Management Handbook* (pp. 23-39): The Fairmont Press, Inc.

Celli, G., Ghiani, E., Pilo, F., & Soma, G. G. (2013). Reliability assessment in smart distribution networks. *Electric Power Systems Research, 104*(0), 164-175. doi: http://dx.doi.org/10.1016/j.epsr.2013.07.001

Chan, D. C. N., Wu, A. M. S., & Hung, E. P. W. (2010). Invulnerability and the intention to drink and drive: An application of the theory of planned behavior. *Accident Analysis & Prevention, 42*(6), 1549-1555. doi: DOI: 10.1016/j.aap.2010.03.011

Chen, S.-M., & Huang, C.-M. (2008). A new approach to generate weighted fuzzy rules using genetic algorithms for estimating null values. *Expert Systems with Applications, 35*(3), 905-917. doi: http://dx.doi.org/10.1016/j.eswa.2007.07.033

Clark, W., & Isherwood, W. (2004). Distributed generation: remote power systems with advanced storage technologies. *Energy Policy, 32*(14), 1573-1589.

Cohen, W. M., & Levinthal, D. A. (1990). Absorptive capacity: a new perspective on learning and innovation. *Administrative science quarterly, 35*(1).

Crossley, P., & Beviz, A. (2010). Smart energy systems: Transitioning renewables onto the grid. *Renewable Energy Focus, 11*(5), 54-59. doi: http://dx.doi.org/10.1016/S1755-0084(10)70118-6

Daioglou, V., van Ruijven, B. J., & van Vuuren, D. P. (2012). Model projections for household energy use in developing countries. *Energy, 37*(1), 601-615. doi: http://dx.doi.org/10.1016/j.energy.2011.10.044

Dall'O', G., Speccher, A., & Bruni, E. (2012). The Green Energy Audit, a new procedure for the sustainable auditing of existing buildings integrated with the LEED Protocols. *Sustainable Cities and Society, 3*(0), 54-65. doi: http://dx.doi.org/10.1016/j.scs.2012.02.001

Darby, S. (2006). The effectiveness of feedback on energy consumption. *A Review for DEFRA of the Literature on Metering, Billing and direct Displays, 486*, 2006.

Davenport, T. H., & Prusak, L. (2000). *Working knowledge: How organizations manage what they know*: Harvard Business Press.

De Young, R. (1996). Some Psychological Aspects of Reduced Consumption Behavior. *Environment and behavior, 28*(3), 358-409. doi: 10.1177/0013916596283005

Dell, R., & Rand, D. A. J. (2001). *Understanding batteries*: Springer Us/Rsc.

DieselService&Supply. (2013). Approximate Diesel Fuel Consumption Chart Retrieved 24 February 2014, from www.dieselserviceandsupply.com/Diesel_Fuel_Consumption.aspx

Dunn, D. S. (2001). Chapter 6: Correlation *Statistics and data analysis for the behavioral sciences*: McGraw-Hill.

Ehrhardt-Martinez, K., Donnelly, K. A., & Laitner, S. (2010). Advanced metering initiatives and residential feedback programs: a meta-review for household electricity-saving opportunities, Report no. E105: American Council for an Energy-Efficient Economy Washington, DC.

Ekren, O., & Ekren, B. Y. (2010). Size optimization of a PV/wind hybrid energy conversion system with battery storage using simulated annealing. *Applied Energy, 87*(2), 592-598. doi: http://dx.doi.org/10.1016/j.apenergy.2009.05.022

Elhadidy, M. A., & Shaahid, S. M. (2000). Parametric study of hybrid (wind + solar + diesel) power generating systems. *Renewable energy, 21*(2), 129-139. doi: http://dx.doi.org/10.1016/S0960-1481(00)00040-9

Ericson, T. (2009). Direct load control of residential water heaters. *Energy Policy, 37*(9), 3502-3512.

Ericson, T. (2011). Households' self-selection of dynamic electricity tariffs. *Applied Energy, 88*(7), 2541-2547. doi: http://dx.doi.org/10.1016/j.apenergy.2011.01.024

Escrivá-Escrivá, G., Santamaria-Orts, O., & Mugarra-Llopis, F. (2012). Continuous assessment of energy efficiency in commercial buildings using energy rating factors. *Energy and Buildings, 49*(0), 78-84. doi: http://dx.doi.org/10.1016/j.enbuild.2012.01.020

ESMAP. (2000). ESMAP Technical Paper 007: Mini-grid Design Manual. *Energy Sector Management Assistance Programme (ESMAP) UNDP/World Bank–April*.

Faruqui, A., Harris, D., & Hledik, R. (2010). Unlocking the €53 billion savings from smart meters in the EU: How increasing the adoption of dynamic tariffs could make or break the EU's smart grid investment. *Energy Policy, 38*(10), 6222-6231. doi: http://dx.doi.org/10.1016/j.enpol.2010.06.010

Faruqui, A., & Sergici, S. (2010). Household response to dynamic pricing of electricity: a survey of 15 experiments. *Journal of Regulatory Economics, 38*(2), 193-225. doi: 10.1007/s11149-010-9127-y

Forward, S. E. (2009). The theory of planned behaviour: The role of descriptive norms and past behaviour in the prediction of drivers' intentions to violate. *Transportation Research Part F: Traffic Psychology and Behaviour, 12*(3), 198-207. doi: DOI: 10.1016/j.trf.2008.12.002

Gao, J., Xiao, Y., Liu, J., Liang, W., & Chen, C. L. P. (2012). A survey of communication/networking in Smart Grids. *Future Generation Computer Systems, 28*(2), 391-404. doi: http://dx.doi.org/10.1016/j.future.2011.04.014

Gellings, C. W. (1985). The concept of demand-side management for electric utilities. *Proceedings of the IEEE, 73*(10), 1468-1470. doi: 10.1109/proc.1985.13318

Gellings, C. W., & Chamberlin, J. H. (1993). Demand-side: Management planning: Lilburn, GA (United States); Fairmont Press, Inc.

Gellings, C. W., & Smith, W. M. (1989). Integrating demand-side management into utility planning. *Proceedings of the IEEE, 77*(6), 908-918.

Ghosh, S., Pipattanasomporn, M., & Rahman, S. (2013, 24-27 Feb. 2013). *Technology deployment status of U.S. smart Grid projects - Electric distribution systems.* Paper presented at the Innovative Smart Grid Technologies (ISGT), 2013 IEEE PES.

Goel, L., Qiuwei, W., Peng, W., & Yi, D. (2005, Nov. 29 2005-Dec. 2 2005). *Reliability enhancement of deregulated power systems considering demand-price elasticity.* Paper presented at the Power Engineering Conference, 2005. IPEC 2005. The 7th International.

Gönen, T. (1986). *Electric power distribution system engineering*: McGraw-Hill New York.

Grover, H. K., & Pretorius, M. W. (2007, 26-28 Sept. 2007). *The technology assessment of demand side bidding within the South African context.* Paper presented at the AFRICON 2007.

Grover, H. K., & Pretorius, M. W. (2008). The technology assessment of demand side bidding in the South African context. *South African Journal of Industrial Engineering, 19*(2), 93-108.

Gyamfi, S., & Krumdieck, S. (2011). Price, environment and security: Exploring multi-modal motivation in voluntary residential peak demand response. *Energy Policy, 39*(5), 2993-3004. doi: http://dx.doi.org/10.1016/j.enpol.2011.03.012

Gyamfi, S., & Krumdieck, S. (2012). Scenario analysis of residential demand response at network peak periods. *Electric Power Systems Research, 93*(0), 32-38. doi: http://dx.doi.org/10.1016/j.epsr.2012.07.004

Gyamfi, S., Krumdieck, S., & Brachkney, L. (2009). Price, Environment and Security: Multi Modal Motivation in Residential Demand Response. Retrieved from

Gyamfi, S., Krumdieck, S., & Brackney, L. (2010). Pattern Recognition Residential Demand Response: An Option for Critical Peak Demand Reduction in New Zealand.

Gyamfi, S., Krumdieck, S., & Urmee, T. (2013). Residential peak electricity demand response—Highlights of some behavioural issues. *Renewable and Sustainable Energy Reviews, 25*(0), 71-77. doi: http://dx.doi.org/10.1016/j.rser.2013.04.006

Haleblian, J., & Finkelstein, S. (1999). The influence of organizational acquisition experience on acquisition performance: A behavioral learning perspective. *Administrative science quarterly, 44*(1), 29-56.

Hamm, A. (2007). *Methodology and Modelling Approach for Strategic Sustainability Analysis of Complex Energy-Environment Systems.* PhD, University of Canterbury.

Hammoudeh, M. A., Mancilla-David, F., Selman, J. D., & Papantoni-Kazakos, P. (2013, 4-5 April 2013). *Communication Architectures for Distribution Networks within the Smart Grid Initiative.* Paper presented at the Green Technologies Conference, 2013 IEEE.

Han, H., Hsu, L.-T., & Sheu, C. (2010). Application of the Theory of Planned Behavior to green hotel choice: Testing the effect of environmental friendly activities. *Tourism Management, 31*(3), 325-334. doi: DOI: 10.1016/j.tourman.2009.03.013

Hausman, D. M., & McPherson, M. S. (2006). *Economic analysis, moral philosophy and public policy*: Cambridge University Press.

He, H. Z., & Kua, H. W. (2013). Lessons for integrated household energy conservation policy from Singapore's southwest Eco-living Program. *Energy Policy, 55*(0), 105-116. doi: http://dx.doi.org/10.1016/j.enpol.2012.10.067

Heberlein, T. A., & Warriner, G. K. (1983). The influence of price and attitude on shifting residential electricity consumption from on- to off-peak periods. *Journal of Economic Psychology, 4*(1-2), 107-130. doi: Doi: 10.1016/0167-4870(83)90048-x

Herter, K. (2007). Residential implementation of critical-peak pricing of electricity. *Energy Policy, 35*(4), 2121-2130.

Hill, L. J. (1991). Residential time-of-use pricing as a load management strategy : Effectiveness and applicability. *Utilities Policy, 1*(4), 308-318.

Ho, Y.-Y., Tsai, H.-T., & Day, J.-d. (2011). Using the theory of planned behaviour to predict public sector training participation. *The Service Industries Journal, 31*(5), 771 - 790.

Hornby, A. S. (2000). Oxford Advanced Learner's Dictionary. Ed. Sally Wehmeier: Oxford: Oxford University Press.

I.E.E. (2012). Utility-scale smart meter deployments, plans, & proposals. IEE Report, May 2012: Institute for Electric Efficiency, The Edison Foundation.

IEA. (2008). *CO2 capture and storage: A key carbon abatement option*: OECD/IEA, Paris.

Ijumba, N. M., & Singh, H. (2004, 15-17 Sept. 2004). *Utilisation of renewable energy sources in deep rural areas.* Paper presented at the AFRICON, 2004. 7th AFRICON Conference in Africa.

Järventausta, P., Repo, S., Rautiainen, A., & Partanen, J. (2010). Smart grid power system control in distributed generation environment. *Annual Reviews in Control, 34*(2), 277-286. doi: http://dx.doi.org/10.1016/j.arcontrol.2010.08.005

Jazayeri, P., Schellenberg, A., Rosehart, W. D., Doudna, J., Widergren, S., Lawrence, D., et al. (2005). A Survey of Load Control Programs for Price and System Stability. *Power Systems, IEEE Transactions on, 20*(3), 1504-1509.

Jeffs, E. (2010). *GREEN ENERGY: Sustainable ELectricity Supply with Low Environmental Impact*: Taylor and Francis Group.

Kabir, G., Abubakar, A. I., & El-Nafaty, U. A. (2010). Energy audit and conservation opportunities for pyroprocessing unit of a typical dry process cement plant. *Energy, 35*(3), 1237-1243. doi: http://dx.doi.org/10.1016/j.energy.2009.11.003

Kaiser, F. G., & Shimoda, T. A. (1999). RESPONSIBILITY AS A PREDICTOR OF ECOLOGICAL BEHAVIOUR. *Journal of Environmental Psychology, 19*(3), 243-253. doi: DOI: 10.1006/jevp.1998.9123

Kalantar, M., & Mousavi G, S. M. (2010). Dynamic behavior of a stand-alone hybrid power generation system of wind turbine, microturbine, solar array and battery storage. *Applied Energy, 87*(10), 3051-3064. doi: http://dx.doi.org/10.1016/j.apenergy.2010.02.019

Kaplani, E., & Kaplanis, S. (2012). A stochastic simulation model for reliable PV system sizing providing for solar radiation fluctuations. *Applied Energy, 97*(0), 970-981. doi: http://dx.doi.org/10.1016/j.apenergy.2011.12.016

Katzev, R. D., & Johnson, T. R. (1983). A social-psychological analysis of residential electricity consumption: the impact of minimal justification techniques. *Journal of Economic Psychology, 3*(3-4), 267-284. doi: Doi: 10.1016/0167-4870(83)90006-5

Kennedy, J., & Eberhart, R. (1995, Nov/Dec 1995). *Particle swarm optimization.* Paper presented at the Neural Networks, 1995. Proceedings., IEEE International Conference on.

Klinge Jacobsen, H. (1998). Integrating the bottom-up and top-down approach to energy–economy modelling: the case of Denmark. *Energy Economics, 20*(4), 443-461. doi: http://dx.doi.org/10.1016/S0140-9883(98)00002-4

Kompridis, N. (2000). So we need something else for reason to mean. *International journal of philosophical studies, 8*(3), 271-295.

Krumdieck, S. (2007). *Feedback control model of regional energy systems.* Paper presented at the IPENZ engineering TreNZ 2007-002.

Krumdieck, S. (2013). Chapter 13. Transition Engineering. In F. Kreith & S. Krumdieck (Eds.), *Principles of Sustainable Energy Systems, 2nd Edition* (2 ed., pp. 693-736): CRC Press, Taylor & Francis Group. (Reprinted from: 2).

Krumdieck, S., & Hamm, A. (2009). Strategic analysis methodology for energy systems with remote island case study. *Energy Policy, 37*(9), 3301-3313. doi: http://dx.doi.org/10.1016/j.enpol.2009.02.005

Kusakana, K., & Vermaak, H. J. (In press). Hybrid diesel generator/renewable energy system performance modeling. *Renewable energy*(0). doi: http://dx.doi.org/10.1016/j.renene.2013.11.025

Kwag, H.-G., & Kim, J.-O. (2012). Optimal combined scheduling of generation and demand response with demand resource constraints. *Applied Energy, 96*(0), 161-170. doi: http://dx.doi.org/10.1016/j.apenergy.2011.12.075

Luce, M. F. (1998). Choosing to avoid: Coping with negatively emotion-laden consumer decisions. *Journal of consumer research, 24*(4), 409-433.

Mansouri, I., Newborough, M., & Probert, D. (1996). Energy consumption in UK households: Impact of domestic electrical appliances. *Applied Energy, 54*(3), 211-285. doi: http://dx.doi.org/10.1016/0306-2619(96)00001-3

Mei, S.-W., & Zhu, J.-Q. (2013). Mathematical and Control Scientific Issues of Smart Grid and Its Prospects. *Acta Automatica Sinica, 39*(2), 119-131. doi: http://dx.doi.org/10.1016/S1874-1029(13)60014-2

Mellit, A., & Benghanem, M. (2007). Sizing of stand-alone photovoltaic systems using neural network adaptive model. *Desalination, 209*(1–3), 64-72. doi: http://dx.doi.org/10.1016/j.desal.2007.04.010

Mellit, A., Kalogirou, S. A., & Drif, M. (2010). Application of neural networks and genetic algorithms for sizing of photovoltaic systems. *Renewable energy, 35*(12), 2881-2893. doi: http://dx.doi.org/10.1016/j.renene.2010.04.017

Merei, G., Berger, C., & Sauer, D. U. (2013). Optimization of an off-grid hybrid PV–Wind–Diesel system with different battery technologies using genetic algorithm. *Solar Energy, 97*(0), 460-473. doi:

http://dx.doi.org/10.1016/j.solener.2013.08.016

Moan, I. S., & Rise, J. Predicting intentions not to "drink and drive" using an extended version of the theory of planned behaviour. *Accident Analysis & Prevention, In Press, Corrected Proof*. doi: DOI: 10.1016/j.aap.2011.02.012

Moghaddam, M. P., Abdollahi, A., & Rashidinejad, M. (2011). Flexible demand response programs modeling in competitive electricity markets. *Applied Energy, 88*(9), 3257-3269. doi: http://dx.doi.org/10.1016/j.apenergy.2011.02.039

Mohamed, M., Krumdieck, S., & Brackney, D. (2010). *Sustainable Renewable Electricity for Small Islands: A Methodology for Essential Load Matching*. Paper presented at the NZSSES, Auckland, New Zealand.

Mohammadi, M., Hosseinian, S. H., & Gharehpetian, G. B. (2012). Optimization of hybrid solar energy sources/wind turbine systems integrated to utility grids as microgrid (MG) under pool/bilateral/hybrid electricity market using PSO. *Solar Energy, 86*(1), 112-125. doi: http://dx.doi.org/10.1016/j.solener.2011.09.011

Moharil, R. M., & Kulkarni, P. S. (2009). A case study of solar photovoltaic power system at Sagardeep Island, India. *Renewable and Sustainable Energy Reviews, 13*(3), 673-681.

Mondal, M. A. H., Kamp, L. M., & Pachova, N. I. (2010). Drivers, barriers, and strategies for implementation of renewable energy technologies in rural areas in Bangladesh--An innovation system analysis. *Energy Policy, 38*(8), 4626-4634.

Mukhopadhyay, S., Soonee, S. K., Joshi, R., & Rajput, A. K. (2012, 22-26 July 2012). *On the progress of renewable energy integration into smart grids in India.* Paper presented at the Power and Energy Society General Meeting, 2012 IEEE.

Mullan, B. A., & Wong, C. L. (2009). Hygienic food handling behaviours. An application of the Theory of Planned Behaviour. *Appetite, 52*(3), 757-761. doi: DOI: 10.1016/j.appet.2009.01.007

Muto, S. (1996, 28 Jan-2 Feb 1996). *A special period peak load forecasting method based on order relations.* Paper presented at the Intelligent Systems Applications to Power Systems, 1996. Proceedings, ISAP '96., International Conference on.

Nejad, M. F., Saberian, A. M., Hizam, H., Radzi, M. A. M., & Ab Kadir, M. Z. A. (2013, 3-4 June 2013). *Application of smart power grid in developing countries.* Paper presented at the Power Engineering and Optimization Conference (PEOCO), 2013 IEEE 7th International.

Nikzad, M., & Mozafari, B. (2014). Reliability assessment of incentive- and priced-based demand response programs in restructured power systems. *International Journal of Electrical Power & Energy Systems, 56*(0), 83-96. doi: http://dx.doi.org/10.1016/j.ijepes.2013.10.007

Nonaka, I. (1994). A dynamic theory of organizational knowledge creation. *Organization science, 5*(1), 14-37.

Parti, M., & Parti, C. (1980). The Total and Appliance-Specific Conditional Demand for Electricity in the Household Sector. *The Bell Journal of Economics, 11*(1), 309-321.

Partovi, F., Nikzad, M., Mozafari, B., & Ranjbar, A. M. (2011). A stochastic security approach to energy and spinning reserve scheduling considering demand response program. *Energy, 36*(5), 3130-3137. doi: http://dx.doi.org/10.1016/j.energy.2011.03.002

Peck, R., & Devore, J. L. (2011). *Statistics: the exploration and analysis of data*: Duxbury Press.

Phillip, S., & Anita, E. (2010). Efficacy of the theory of planned behaviour model in predicting safe food handling practices. *Food Control, 21*(7), 983-987. doi: DOI: 10.1016/j.foodcont.2009.12.012

Qureshi, W. A., Nair, N.-K. C., & Farid, M. M. (2011). Impact of energy storage in buildings on electricity demand side management. *Energy Conversion and Management, 52*(5), 2110-2120. doi: http://dx.doi.org/10.1016/j.enconman.2010.12.008

Rankin, R., & Rousseau, P. G. (2008). Demand side management in South Africa at industrial residence water heating systems using in line water heating methodology. *Energy Conversion and Management, 49*(1), 62-74. doi: http://dx.doi.org/10.1016/j.enconman.2007.05.022

Rehman, S., & Al-Hadhrami, L. M. (2010). Study of a solar PV–diesel–battery hybrid power system for a remotely located population near Rafha, Saudi Arabia. *Energy, 35*(12), 4986-4995. doi: http://dx.doi.org/10.1016/j.energy.2010.08.025

Richardson, I., Thomson, M., Infield, D., & Clifford, C. (2010). Domestic electricity use: A high-resolution energy demand model. *Energy and Buildings, 42*(10), 1878-1887.

Rosas-Flores, J. A., & Gálvez, D. M. (2010). What goes up: Recent trends in Mexican residential energy use. *Energy, 35*(6), 2596-2602. doi: http://dx.doi.org/10.1016/j.energy.2010.01.015

Sa, x, nchez, V., Ramirez, J. M., & Arriaga, G. (2010, 14-17 March 2010). *Optimal sizing of a hybrid renewable system.* Paper presented at the Industrial Technology (ICIT), 2010 IEEE International Conference on.

Saha, G. P., & Stephenson, J. (1980). A model of residential energy use in New Zealand. *Energy, 5*(2), 167-175. doi: Doi: 10.1016/0360-5442(80)90005-5

Saidur, R., Rahim, N. A., Masjuki, H. H., Mekhilef, S., Ping, H. W., & Jamaluddin, M. F. (2009). End-use energy analysis in the Malaysian industrial sector. *Energy, 34*(2), 153-158. doi: http://dx.doi.org/10.1016/j.energy.2008.11.004

Santamouris, M., Balaras, C. A., Dascalaki, E., Argiriou, A., & Gaglia, A. (1996). Energy conservation and retrofitting potential in Hellenic hotels. *Energy and Buildings, 24*(1), 65-75. doi: http://dx.doi.org/10.1016/0378-7788(95)00963-9

Segurado, R., Krajačić, G., Duić, N., & Alves, L. (2011). Increasing the penetration of renewable energy resources in S. Vicente, Cape Verde. *Applied Energy, 88*(2), 466-472. doi: http://dx.doi.org/10.1016/j.apenergy.2010.07.005

Shaahid, S. M., & Elhadidy, M. A. (2007). Technical and economic assessment of grid-independent hybrid photovoltaic–diesel–battery power systems for commercial loads in desert environments. *Renewable and Sustainable Energy Reviews, 11*(8), 1794-1810. doi: http://dx.doi.org/10.1016/j.rser.2006.03.001

Shafir, E., Simonson, I., & Tversky, A. (1993). Reason-based choice. *Cognition, 49*(1), 11-36.

Shaikh, S. K. M., & Dharme, A. A. (2009, 27-29 Dec. 2009). *Time of Use pricing - India, a case study.* Paper presented at the Power Systems, 2009. ICPS '09. International Conference on.

Shen, B., Price, L., & Lu, H. (2012). Energy audit practices in China: National and local experiences and issues. *Energy Policy, 46*(0), 346-358. doi: http://dx.doi.org/10.1016/j.enpol.2012.03.069

Singh, A. (2012). The Indian Navy's New'Expeditionary'Outlook: Observer Research Foundation, New Delhi, India.

Smith, J. L. (2009). World Oil: Market or Mayhem? *The Journal of Economic Perspectives, 23*(3), 145-164. doi: 10.2307/27740545

Smith, K. G., Collins, C. J., & Clark, K. D. (2005). Existing knowledge, knowledge creation capability, and the rate of new product introduction in high-technology firms. *Academy of Management Journal, 48*(2), 346-357.

Spees, K., & Lave, L. B. (2007). Demand Response and Electricity Market Efficiency. *The Electricity Journal, 20*(3), 69-85.

Strbac, G. (2008). Demand side management: Benefits and challenges. *Energy Policy, 36*(12), 4419-4426. doi: DOI: 10.1016/j.enpol.2008.09.030

Su, W. F., Huang, S. J., & Lin, C. E. (2001). Economic analysis for demand-side hybrid photovoltaic and battery energy storage system. *Industry Applications, IEEE Transactions on, 37*(1), 171-177.

Sung-Yong, S., & Beom-Jin, C. (2009, 26-30 Oct. 2009). *A Korean Smart Grid architecture design for a field test based on power IT.* Paper presented at the Transmission & Distribution Conference & Exposition: Asia and Pacific, 2009.

Sureshkumar, U., Manoharan, P. S., & Ramalakshmi, A. P. S. (2012, 30-31 March 2012). *Economic cost analysis of hybrid renewable energy system using HOMER.* Paper presented at the Advances in Engineering, Science and Management (ICAESM), 2012 International Conference on.

Tan, X., Li, Q., & Wang, H. (2013). Advances and trends of energy storage technology in Microgrid. *International Journal of Electrical Power & Energy Systems, 44*(1), 179-191. doi: http://dx.doi.org/10.1016/j.ijepes.2012.07.015

Tester, J. W., Drake, E. M., Driscoll, M. J., Golay, M. W., & Peters, W. A. (2005). *Sustainable Energy: Choosing Among Options*. Cambridge, Massachusettes: MIT Press.

Thomas, P. C., Natarajan, B., & Anand, S. (1991). Energy conservation guidelines for government office buildings in New Delhi. *Energy and Buildings, 16*(1–2), 617-623. doi: http://dx.doi.org/10.1016/0378-7788(91)90030-7

Thumann, A., & Younger, W. J. (2008). Chapter 1 Energy auditing basics *Handbook of energy audits*: The Fairmont Press, Inc.

Tishler, A., & Ye, Y. (1993). Minimal adjustment costs, factor demands, and seasonal time-of-use electricity rates. *Resource and Energy Economics, 15*(3), 313-335. doi: Doi: 10.1016/0928-7655(93)90011-i

Tonglet, M., Phillips, P. S., & Read, A. D. (2004). Using the Theory of Planned Behaviour to investigate the determinants of recycling behaviour: a case study from Brixworth, UK. *Resources, Conservation and Recycling, 41*(3), 191-214. doi: DOI: 10.1016/j.resconrec.2003.11.001

Trianti-Stourna, E., Spyropoulou, K., Theofylaktos, C., Droutsa, K., Balaras, C. A., Santamouris, M., et al. (1998). Energy conservation strategies for sports centers: Part A. Sports halls. *Energy and Buildings, 27*(2), 109-122. doi: http://dx.doi.org/10.1016/S0378-7788(97)00040-6

Ueckerdt, F., Hirth, L., Luderer, G., & Edenhofer, O. (2013). System LCOE: What are the costs of variable renewables? *Energy, 63*(0), 61-75. doi: http://dx.doi.org/10.1016/j.energy.2013.10.072

Ueno, T., Inada, R., Saeki, O., & Tsuji, K. (2006a). Effectiveness of an energy-consumption information system for residential buildings. *Applied Energy, 83*(8), 868-883.

Ueno, T., Sano, F., Saeki, O., & Tsuji, K. (2006b). Effectiveness of an energy-consumption information system on energy savings in residential houses based on monitored data. *Applied Energy, 83*(2), 166-183.

Underwood, C. P., Ramachandran, J., Giddings, R. D., & Alwan, Z. (2007). Renewable-energy clusters for remote communities. *Applied Energy, 84*(6), 579-598.

Ural, O. (1980 (a)). *Vol. 1.* Paper presented at the Energy Resources and Conservation Related to Built Environment: Proceedings of the International Conference on Energy Resources and Conservation Related to Built Environment, December 7-12, 1980, Miami, Florida, pp. 365 - 369.

Ural, O. (1980 (b)). *Vol. 2.* Paper presented at the Energy Resources and Conservation Related to Built Environment: Proceedings of the International Conference on Energy Resources and Conservation Related to Built Environment, December 7-12, 1980, Miami, Florida, pp. 598 - 611.

Urbanetz, J., Braun, P., & Rüther, R. (2012). Power quality analysis of grid-connected solar photovoltaic generators in Brazil. *Energy Conversion and Management, 64*(0), 8-14. doi: http://dx.doi.org/10.1016/j.enconman.2012.05.008

USDOE. (2006). Benefits of Demand Response in Electricity Markets and Recommendations for achieving them (DOE, Trans.). US: DOE.

Uslar, M., Rohjans, S., & Specht, M. (2012). Technical Requirements for DER Integration Architectures. *Energy Procedia, 20*(0), 281-290. doi: http://dx.doi.org/10.1016/j.egypro.2012.03.028

Valenzuela, J., Thimmapuram, P. R., & Kim, J. (2012). Modeling and simulation of consumer response to dynamic pricing with enabled technologies. *Applied Energy, 96*(0), 122-132. doi: http://dx.doi.org/10.1016/j.apenergy.2011.11.022

van Alphen, K., van Sark, W. G. J. H. M., & Hekkert, M. P. (2007). Renewable energy technologies in the Maldives--determining the potential. *Renewable and Sustainable Energy Reviews, 11*(8), 1650-1674.

Vassileva, I., Odlare, M., Wallin, F., & Dahlquist, E. (2012). The impact of consumers' feedback preferences on domestic electricity consumption. *Applied Energy, 93*(0), 575-582. doi: http://dx.doi.org/10.1016/j.apenergy.2011.12.067

Wang, W., Xu, Y., & Khanna, M. (2011). A survey on the communication architectures in smart grid. *Computer Networks, 55*(15), 3604-3629. doi: http://dx.doi.org/10.1016/j.comnet.2011.07.010

Weiding, B. L., Yiqun, P., Cunyang, F., Lei, X., & Xin, H. (1998). Analysis of energy consumption status and energy efficiency potentials in commercial buildings of Shanghai [J]. *Hv & Ac, 6*.

Welding, L. (1996). Shanghai: building energy conservation and cooling & heating sources of air conditioning [J]. *Hv & Ac, 4*.

Wood, G., & Newborough, M. (2007). Energy-use information transfer for intelligent homes: Enabling energy conservation with central and local displays. *Energy and Buildings, 39*(4), 495-503. doi: http://dx.doi.org/10.1016/j.enbuild.2006.06.009

Worrall, N. (2006). *Analysis of providing affordable electricity supply for the outer islands in the Maldives.* University of Southern Queensland.

Yang, H., Wei, Z., & Chengzhi, L. (2009). Optimal design and techno-economic analysis of a hybrid solar–wind power generation system. *Applied Energy, 86*(2), 163-169. doi: http://dx.doi.org/10.1016/j.apenergy.2008.03.008

Yannas, S. (1996). Energy indices and performance targets for housing design. *Energy and Buildings, 23*(3), 237-249. doi: http://dx.doi.org/10.1016/0378-7788(95)00949-3

Zhang, X., Tan, S.-C., Li, G., Li, J., & Feng, Z. (2013). Components sizing of hybrid energy systems via the optimization of power dispatch simulations. *Energy, 52*(0), 165-172. doi: http://dx.doi.org/10.1016/j.energy.2013.01.013

Zhou, X., Yan, J., Zhu, J., & Cai, P. (2013). Survey of energy consumption and energy conservation measures for colleges and universities in Guangdong province. *Energy and Buildings, 66*(0), 112-118. doi: http://dx.doi.org/10.1016/j.enbuild.2013.07.055

Zhou, Z., Zhang, J., Liu, P., Li, Z., Georgiadis, M. C., & Pistikopoulos, E. N. (2013). A two-stage stochastic programming model for the optimal design of distributed energy systems. *Applied Energy, 103*(0), 135-144. doi: http://dx.doi.org/10.1016/j.apenergy.2012.09.019

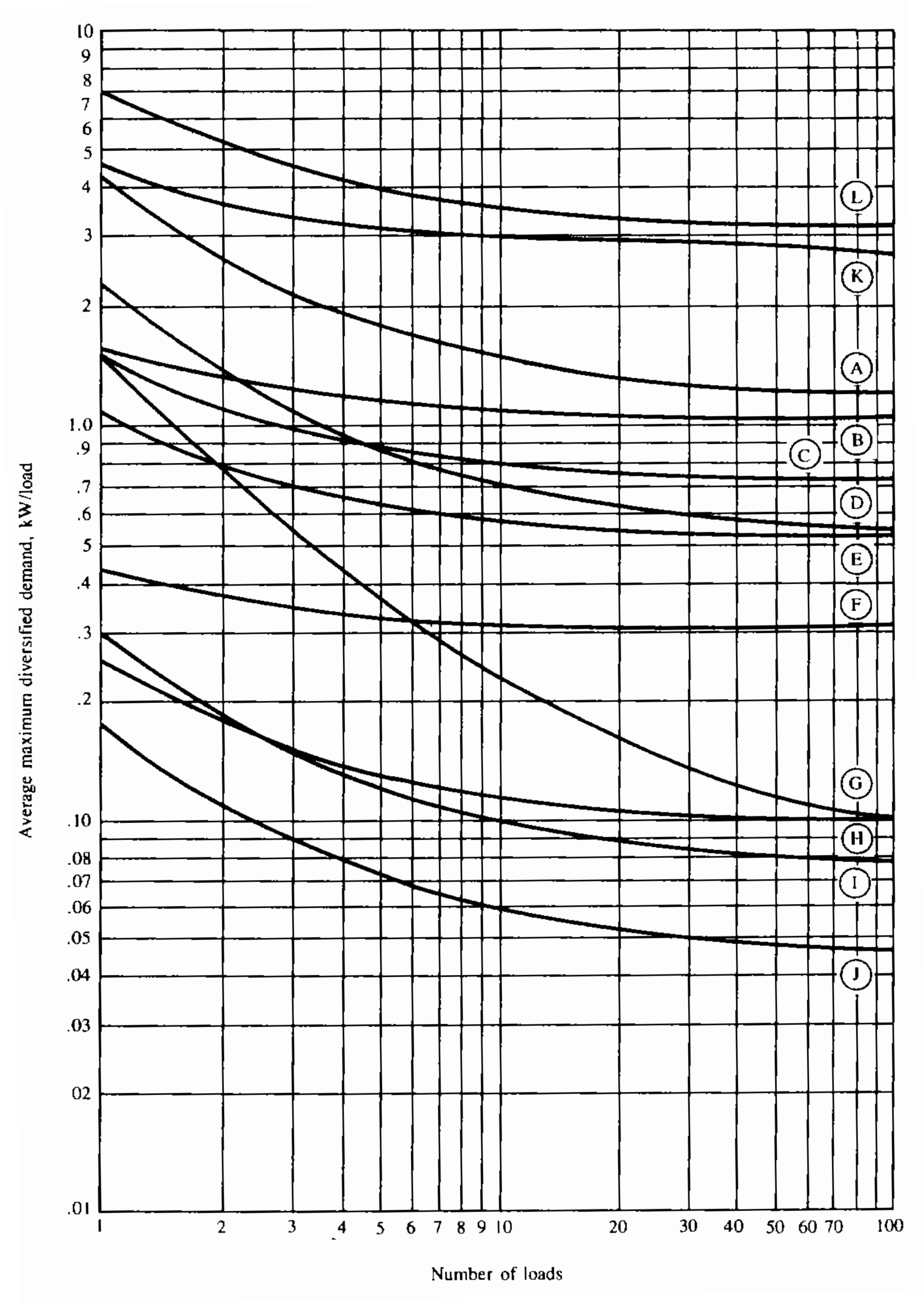
Zhu, Y. (2006). Applying computer-based simulation to energy auditing: A case study. *Energy and Buildings, 38*(5), 421-428. doi: http://dx.doi.org/10.1016/j.enbuild.2005.07.007

APPENDICES

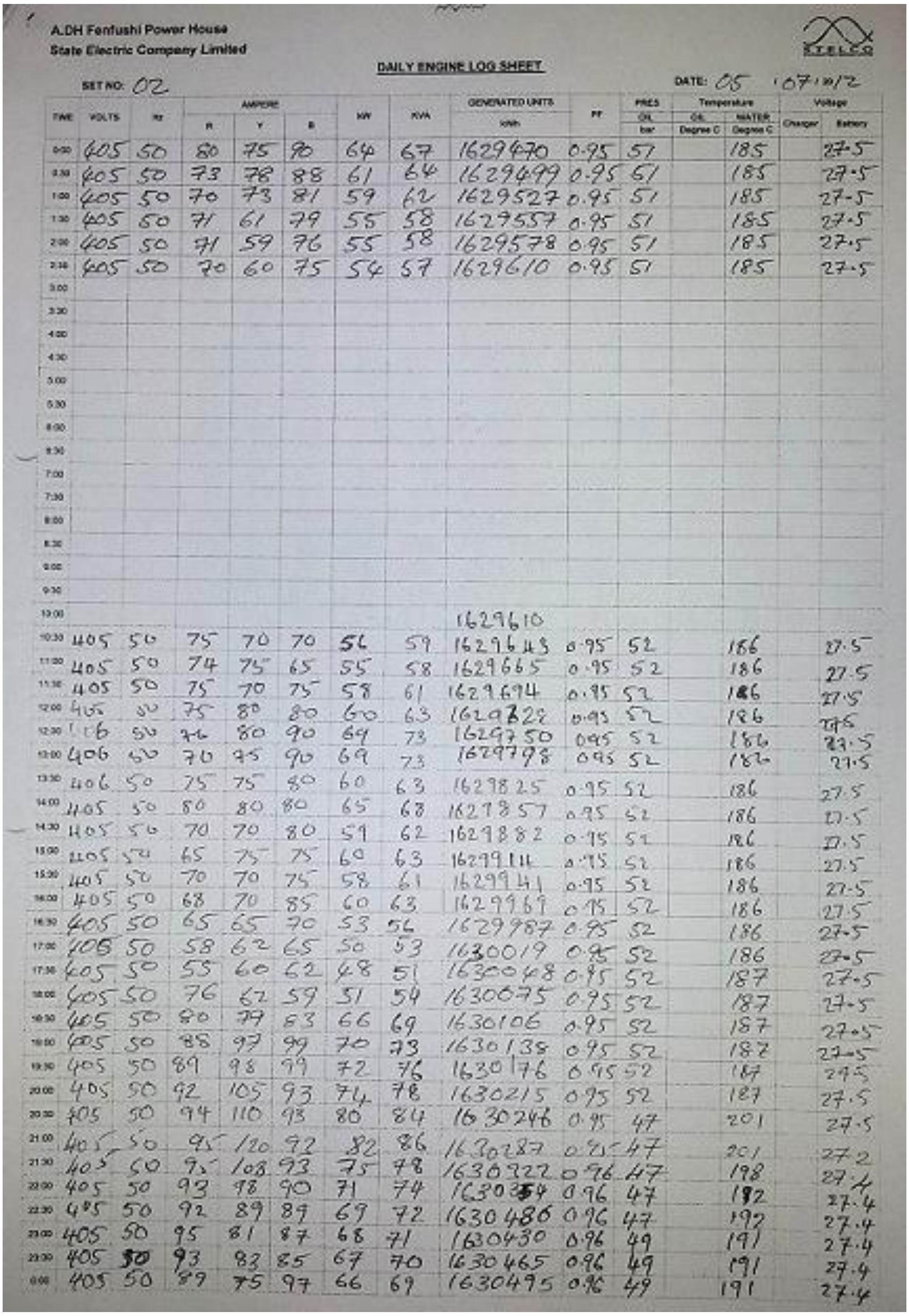
A1. Hourly Variation Factors calculated by (Gönen, 1986) for different household items

Hour	Lighting and misc.	Refrigerator	Home freezer	Range	Air conditioning	Heat pump		House heating	Water heater			Clothes dryer
						Cooling season	Heating season		OPWH		Uncontrolled	
									Both elements restructured	Only bottom elements restructured		
12 A.M.	0.32	0.93	0.92	0.02	0.40	0.42	0.34	0.11	0.41	0.61	0.51	0.03
1	0.12	0.89	0.90	0.01	0.39	0.35	0.49	0.07	0.33	0.46	0.37	0.02
2	0.10	0.80	0.87	0.01	0.36	0.35	0.51	0.09	0.25	0.34	0.30	0.00
3	0.09	0.76	0.85	0.01	0.35	0.28	0.54	0.08	0.17	0.24	0.22	0.00
4	0.08	0.79	0.82	0.01	0.35	0.28	0.57	0.13	0.13	0.19	0.15	0.00
5	0.10	0.72	0.84	0.02	0.33	0.26	0.63	0.15	0.13	0.19	0.14	0.00
6	0.19	0.75	0.85	0.05	0.30	0.26	0.74	0.17	0.17	0.24	0.16	0.00
7	0.41	0.75	0.85	0.30	0.41	0.35	1.00	0.76	0.27	0.37	0.46	0.00
8	0.35	0.79	0.86	0.47	0.53	0.49	0.91	1.00	0.47	0.65	0.70	0.08
9	0.31	0.79	0.86	0.28	0.62	0.58	0.83	0.97	0.63	0.87	1.00	0.20
10	0.31	0.79	0.87	0.22	0.72	0.70	0.74	0.68	0.67	0.93	1.00	0.65
11	0.30	0.85	0.90	0.22	0.74	0.73	0.60	0.57	0.67	0.93	0.99	1.00
12 noon	0.28	0.85	0.92	0.33	0.80	0.84	0.57	0.55	0.67	0.93	0.98	0.98
1	0.26	0.87	0.96	0.25	0.86	0.88	0.49	0.51	0.61	0.85	0.86	0.70
2	0.29	0.90	0.98	0.16	0.89	0.95	0.46	0.49	0.55	0.76	0.82	0.65
3	0.30	0.90	0.99	0.17	0.96	1.00	0.40	0.48	0.49	0.68	0.81	0.63
4	0.32	0.90	1.00	0.24	0.97	1.00	0.43	0.44	0.33	0.46	0.79	0.38
5	0.70	0.90	1.00	0.80	0.99	1.00	0.43	0.79	0.00	0.09	0.75	0.30
6	0.92	0.90	0.99	1.00	1.00	1.00	0.49	0.88	0.00	0.13	0.75	0.22
7	1.00	0.95	0.98	0.30	0.91	0.88	0.51	0.76	0.00	0.19	0.80	0.26
8	0.95	1.00	0.98	0.12	0.79	0.71	0.60	0.54	1.00	1.00	0.81	0.20
9	0.85	0.95	0.97	0.09	0.71	0.72	0.54	0.42	0.84	0.98	0.73	0.18
10	0.72	0.88	0.96	0.05	0.64	0.53	0.51	0.27	0.67	0.77	0.67	0.10
11	0.50	0.88	0.95	0.04	0.55	0.49	0.34	0.23	0.54	0.69	0.59	0.04

A2. Average diversified demand variations with respect to the number of residential loads (Source: (Gönen, 1986))



A3. Fenfushi island powerhouse daily data log sheet



A.DH Fenfushi Power House
State Electric Company Limited

STELCO

DAILY ENGINE LOG SHEET

SET NO: 02

DATE: 05 / 07 / 2012

TIME	VOLTS	Hz	AMPERE R	AMPERE Y	AMPERE B	KW	KVA	GENERATED UNITS kWh	PF	PRES OIL bar	Temperature OIL Degree C	Temperature WATER Degree C	Voltage Charger	Voltage Battery
0:00	405	50	80	75	90	64	67	1629470	0.95	57		185		27.5
0:30	405	50	73	78	88	61	64	1629499	0.95	51		185		27.5
1:00	405	50	70	73	81	59	62	1629527	0.95	51		185		27.5
1:30	405	50	71	61	79	55	58	1629557	0.95	51		185		27.5
2:00	405	50	71	59	76	55	58	1629578	0.95	51		185		27.5
2:30	405	50	70	60	75	54	57	1629610	0.95	51		185		27.5
3:00														
3:30														
4:00														
4:30														
5:00														
5:30														
6:00														
6:30														
7:00														
7:30														
8:00														
8:30														
9:00														
9:30														
10:00								1629610						
10:30	405	50	75	70	70	56	59	1629643	0.95	52		186		27.5
11:00	405	50	74	75	65	55	58	1629665	0.95	52		186		27.5
11:30	405	50	75	70	75	58	61	1629694	0.95	52		186		27.5
12:00	405	50	75	80	80	60	63	1629722	0.95	52		186		27.5
12:30	406	50	76	80	90	69	73	1629750	0.95	52		186		27.5
13:00	406	50	70	75	90	69	73	1629798	0.95	52		186		27.5
13:30	406	50	75	75	80	60	63	1629825	0.95	52		186		27.5
14:00	405	50	80	80	80	65	68	1629857	0.95	52		186		27.5
14:30	405	50	70	70	80	59	62	1629882	0.95	52		186		27.5
15:00	405	50	65	75	75	60	63	1629914	0.95	52		186		27.5
15:30	405	50	70	70	75	58	61	1629941	0.95	52		186		27.5
16:00	405	50	68	70	85	60	63	1629969	0.95	52		186		27.5
16:30	405	50	65	65	70	53	56	1629987	0.95	52		186		27.5
17:00	405	50	58	62	65	50	53	1630019	0.95	52		186		27.5
17:30	405	50	55	60	62	48	51	1630048	0.95	52		187		27.5
18:00	405	50	76	62	59	51	54	1630075	0.95	52		187		27.5
18:30	405	50	80	79	83	66	69	1630106	0.95	52		187		27.5
19:00	405	50	88	97	99	70	73	1630138	0.95	52		187		27.5
19:30	405	50	89	98	99	72	76	1630176	0.95	52		187		27.5
20:00	405	50	92	105	93	74	78	1630215	0.95	52		187		27.5
20:30	405	50	94	110	93	80	84	1630246	0.95	47		201		27.5
21:00	405	50	95	120	92	82	86	1630287	0.95	47		201		27.2
21:30	405	50	95	108	93	75	78	1630322	0.96	47		198		27.4
22:00	405	50	93	98	90	71	74	1630354	0.96	47		192		27.4
22:30	405	50	92	89	89	69	72	1630486	0.96	47		192		27.4
23:00	405	50	95	81	87	68	71	1630430	0.96	49		191		27.4
23:30	405	50	93	83	85	67	70	1630465	0.96	49		191		27.4
0:00	405	50	89	75	97	66	69	1630495	0.96	49		191		27.4

A4. Adaptability survey questionnaire

Department of Mechanical Engineering

Advanced Energy and Material Systems Lab

University of Canterbury
Te Whare Wānganga o Waitaha
Private Bag 4800
Christchurch 8020, New Zealand

Telephone: +64-3-364 2987
Facsimile: +64-3-364 2078
Website: www.mech.canterbury.ac.nz

UNIVERSITY OF CANTERBURY
Te Whare Wānanga o Waitaha
CHRISTCHURCH NEW ZEALAND

The aim of this questionnaire is to understand the energy (mainly electricity) usage pattern of typical island communities of the Maldives, their willingness and ability to adjust their power consumption, especially in an energy constraint or an emergency situation

I - Household Information

1 What year was your house built? ☐

2 How many people live in your household? ☐

3 How many bedrooms does your house have? ☐

4 How many living rooms does your house have? ☐

5 Does the house have a "well" that can be used manually?

☐ YES ☐ NO

8 What material is used for roofing? ☐

9 How many windows does the house have? ☐

10 Does the house have a ceiling?

☐ YES ☐ NO

II - Power Cost

11 Approximately how much is your monthly electricity bill? MRf ☐

12 What price do you pay per unit (kWh) of electricity? MRf ☐

III - Household Energy

13 What cooling appliances do you have?

☐ Fan ☐ A/C

14 In your opinion, which household appliance is responsible for the largest share of the bill?

☐ A/C ☐ Fridge ☐ Oven ☐ Microwave

☐ Washing Machine ☐ Other (Specify):

VII -Fuel and Environmental Concerns

24 Do you know what kind of fuel is being used for power generation?

☐ NO ☐ YES (Specify) : ....

25 How do you think the fuel is being transported to the island?

26 Have you ever had any incidents concerning oil spills?

☐ NO ☐ YES (Specify below)

27 What other forms of pollution would you consider to be linked to the power generation?

☐ Smoke ☐ Sound ☐ Carbon-dioxide

☐ Others (Comment below)

28 Do you think use of renewable energy would be a solution for the environmental concerns?

☐ YES ☐ NO

(comment)

IX - Energy Constraint Situation Or Power Genertion Shortage

It can be seen that the main source of electrical power for the island is Diesel Generators and the diesel fuel had only been transported to the island by Sea Transport. Latest statistical facts show that diesel fuel prices has been varying a lot during the last few years and it had been rising since 1970's. Apart from the diesel prices the mode of transport of diesel in to the island opens a whole new set of vulnarabilities for the electrical power generation. Considering the possibilities of getting a situtation that could disrupt the normal power generation, please answer the following questions.

29 In case of a power generation shortage, what electrical appliances can you "STOP" using until the end of the situation?

☐ Air Conditioning ☐ Iron ☐ Water Pump

☐ Washing Machine ☐ Oven ☐ Television Sets

☐ Microwave Oven ☐ Others (Specify below)

IV - In a typical weekday

15 What time does your day start? ☐

16 What are your first activities?

☐

V - Electrical Price Concerns

17 How concerned are you about the cost of your electricity bills?

Not concerned					Very much concerned				
1	2	3	4	5	6	7	8	9	10

18 Do you take any energy conservation measures?

☐ NO ☐ YES (Please Specify)

☐

19 If your electricity prices are to go up, what percentage increase above your last bill would you consider to be too high?

☐ 10% ☐ 20% ☐ 30%

☐ 40% ☐ 50% ☐ Above 50%

VI - Electrical Energy Security Concerns

20 In the past couple of months, have you had any power outages?

☐ YES ☐ NO

21 If you have had any power outages, what do you think was the cause of it?

☐

22 How many power outages a week, would you consider to be too many?

☐ 7 ☐ 6 ☐ 5 ☐ 4

☐ 3 ☐ 2 ☐ 1

23 If the power has to be cut, how many hours would you consider too long?

☐ < 1 hour ☐ 1 hour ☐ 2 hours ☐ 3 hours or more

30 In case of a power generation shortage, what is the maximum number of lights you are willing to use until the situation has ended? ☐

31 What is the percentage by which you can reduce (if possible) the use of electrical fans, until the situation has ended?

☐ 10% ☐ 20% ☐ 30% ☐ 40%

☐ 50% ☐ More than 50% ☐ Others (Specify): ....

32 What are the appliances which you consider as the most essential or those appliances which if "Turned OFF" will disrupt the health and wellbeing of the family.

☐ Fans ☐ Iron ☐ Water Pump

☐ Lights ☐ Others (Specify below)

X - Information received from the Electric Power Supplier

33 How well do you know about the operation of the power system in the island?

Not at all								Very well	
1	2	3	4	5	6	7	8	9	10

34 Considering the last time when you had the power cut, how well were you informed about what had happened?

Not at all								Very well	
1	2	3	4	5	6	7	8	9	10

35 Do you believe that you could better manage the use of electrical appliances if you are being informed about the supply side difficulties ?

☐ YES ☐ NO

36 In case of an Emergency situation which has been discussed before, how would you prefer the power supplier to inform you?

☐ Visual Aids (Colour Signs) ☐ Text Message (Phone No.): ....

☐ Others (Specify) : ....

A5. Approximate fuel consumption rates of different rated generators (Source: (DieselService&Supply, 2013))

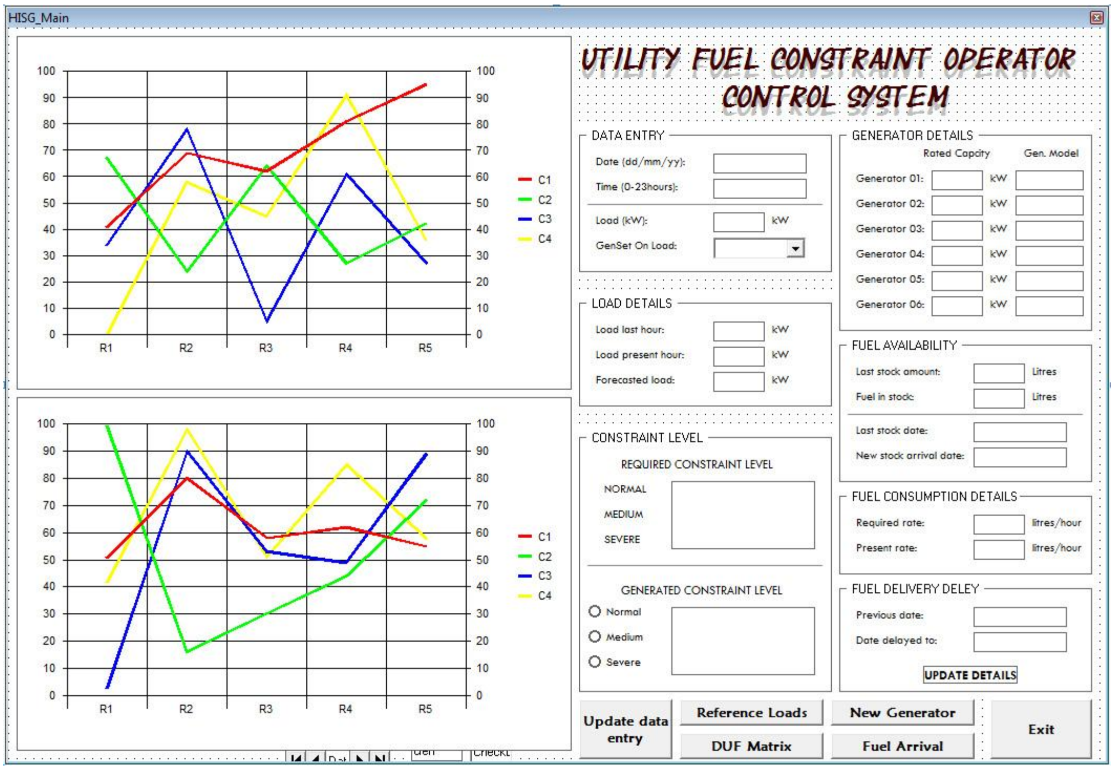
Generator Size (kW)	1/4 Load		1/2 Load		3/4 Load		Full load	
	gal/hr	liter/hr	gal/hr	liter/hr	gal/hr	liter/hr	gal/hr	liter/hr
20	0.6	2.3	0.9	3.4	1.3	4.9	1.6	6.1
30	1.3	4.9	1.8	6.8	2.4	9.1	2.9	11.0
40	1.6	6.1	2.3	8.7	3.2	12.1	4.0	15.1
60	1.8	6.8	2.9	11.0	3.8	14.4	4.8	18.2
75	2.4	9.1	3.4	12.9	4.6	17.4	6.1	23.1
100	2.6	9.8	4.1	15.5	5.8	22.0	7.4	28.0
125	3.1	11.7	5.0	18.9	7.1	26.9	9.1	34.4
135	3.3	12.5	5.4	20.4	7.6	28.8	9.8	37.1
150	3.6	13.6	5.9	22.3	8.4	31.8	10.9	41.3
175	4.1	15.5	6.8	25.7	9.7	36.7	12.7	48.1
200	4.7	17.8	7.7	29.1	11.0	41.6	14.4	54.5
230	5.3	20.1	8.8	33.3	12.5	47.3	16.6	62.8
250	5.7	21.6	9.5	36.0	13.6	51.5	18.0	68.1
300	6.8	25.7	11.3	42.8	16.1	60.9	21.5	81.4
350	7.9	29.9	13.1	49.6	18.7	70.8	25.1	95.0
400	8.9	33.7	14.9	56.4	21.3	80.6	28.6	108.3
500	11.0	41.6	18.5	70.0	26.4	99.9	35.7	135.1
600	13.2	50.0	22.0	83.3	31.5	119.2	42.8	162.0
750	16.3	61.7	27.4	103.7	39.3	148.8	53.4	202.1
1000	21.6	81.8	36.4	137.8	52.1	197.2	71.1	269.1
1250	26.9	101.8	45.3	171.5	65.0	246.1	88.8	336.1
1500	32.2	121.9	54.3	205.5	77.8	294.5	106.5	403.1
1750	37.5	142.0	63.2	239.2	90.7	343.3	124.2	470.1
2000	42.8	162.0	72.2	273.3	103.5	391.8	141.9	537.1
2250	48.1	182.1	81.1	307.0	116.4	440.6	159.6	604.2

A6. Number of general household appliances used by the surveyed households in Fenfushi island

Household code	Florescent / Energy Saving Lights	Incandescent Lights	Fan	Fridge/Freezer	Blender/Mixer	Microwave	Oven	Toaster	Rice Cooker	Stove	Kettle	Sandwich Maker	Colour T/V	VCR/DVD player	Radio/Cassette	Computer	Monitor	Laptop	Sewing Machine	Air Conditioner	Hair Dryer	Shaver	Washing Machine	Iron	Water Pump	Electric Insect Repellent	Decoder (Airtel)	Emergency Lights	Exhaust Fan
1001	17	5	12	1	1	0	1	1	1	0	2	0	1	3	0	2	2	0	1	0	0	0	5	2	2	4	1	2	0
1002	29	3	10	3	1	1	1	1	1	0	1	0	2	1	0	2	2	0	1	3	0	1	4	1	2	3	0	0	0
1003	9	3	6	1	2	0	0	1	1	2	1	1	1	1	0	0	0	1	1	0	0	0	1	1	1	1	0	0	0
1004	33	4	13	2	3	1	1	1	1	0	1	1	4	1	2	0	0	1	1	0	0	0	1	3	1	3	0	0	5
1005	20	5	7	1	1	1	1	2	0	0	2	1	3	0	0	1	1	0	1	2	1	0	2	2	1	3	0	0	1
1006	8	5	6	1	1	1	0	1	1	0	1	1	4	3	0	0	0	0	0	1	1	0	2	1	2	2	0	2	0
1007	30	6	9	2	1	1	0	1	0	0	0	1	4	2	0	0	0	3	2	1	0	1	2	2	1	2	0	0	4
1008	20	5	8	1	2	1	0	1	1	0	1	1	4	0	0	0	0	1	1	0	0	1	1	2	1	3	0	0	0
1009	12	5	7	1	1	1	0	1	1	0	1	0	2	2	0	0	0	3	1	2	0	0	1	1	1	4	0	0	1
1010	34	4	10	1	1	1	0	1	1	0	1	1	3	2	0	0	0	2	1	1	0	0	1	2	1	0	0	0	2
1011	9	0	6	1	1	1	0	1	1	0	1	1	1	0	0	0	0	1	0	0	0	1	1	1	1	0	0	0	0
1012	18	4	7	1	1	1	0	1	1	1	1	1	3	1	0	0	0	1	1	0	0	0	1	2	1	1	0	0	0
1013	16	3	8	2	1	0	1	1	1	0	0	1	2	0	0	2	2	0	1	0	0	2	1	1	1	0	0	0	1
1014	16	4	6	1	1	0	1	1	1	0	1	1	2	1	0	1	1	0	1	0	1	1	1	1	1	0	0	0	0
1015	16	4	7	1	1	0	1	0	1	0	0	1	3	2	0	0	0	0	1	0	0	0	1	1	1	6	0	0	0
1016	21	5	7	1	1	0	1	1	1	1	1	0	4	2	0	1	1	1	1	0	0	1	1	2	1	3	0	0	0
1017	17	6	8	1	1	1	0	1	1	0	1	1	0	0	1	0	0	1	1	2	2	1	1	2	1	3	0	5	3
1018	22	3	6	2	2	0	1	1	0	0	1	0	1	1	0	0	0	2	1	2	0	1	1	1	1	0	0	0	1
1019	16	1	9	1	1	1	0	1	0	0	0	0	1	0	0	1	1	0	0	2	0	1	1	2	2	3	0	0	1
1020	11	2	4	1	1	0	0	1	0	0	0	0	1	1	0	0	0	0	0	0	0	0	1	1	1	0	0	0	0
1021	22	4	8	1	1	1	0	1	1	1	0	0	1	1	1	0	0	0	1	1	0	0	2	1	1	1	0	0	4
1022	13	3	5	1	1	1	0	0	0	0	0	0	1	0	0	1	1	0	0	0	0	0	1	1	1	2	0	0	1
1023	11	2	4	1	1	1	0	1	1	0	0	1	1	1	1	0	0	0	1	0	0	0	1	2	1	0	0	0	0
1024	5	0	5	0	1	1	0	1	1	0	0	0	1	1	0	0	0	0	1	0	0	1	1	1	0	1	0	0	0
1025	34	1	10	1	1	0	0	1	1	1	0	0	2	1	0	0	0	0	0	1	0	0	1	1	2	4	0	0	0
1026	19	5	7	1	1	1	0	1	1	1	2	0	0	0	1	0	0	2	1	2	1	0	1	2	1	2	0	0	0
1027	8	3	4	1	1	1	0	1	1	0	0	0	1	1	0	0	0	0	1	0	0	0	1	1	0	1	0	0	0
1028	18	4	8	1	1	0	0	0	0	0	1	0	1	1	0	0	0	4	1	0	1	3	1	1	1	1	0	0	3
1029	23	10	9	1	1	0	0	1	2	0	1	1	2	2	0	0	0	0	0	1	0	1	1	1	1	1	0	0	0
1030	16	3	6	1	1	1	0	1	0	0	1	1	1	1	0	1	1	1	1	1	1	0	1	1	1	1	0	0	0

A7. UFCOCS screenshots and code

MAIN SCREEN



VB CODE FOR THIS FORM:

```
Public chktol As Double

Public chktolasone As Double

Public chksevere As Double

Public fueltime As Double

Public FSAD As Double

Public LoadTime As Double


Private Sub cmdDUFMatrix_Click()

   frmDUFMatrix.Show

End Sub


Private Sub cmdExit_Click()

   ' Close all and exit program
```

```
   Close All
   End
End Sub
Private Sub cmdNewGenerator_Click()
   'Load the new Generator form
   frmNewGenerator.Show
End Sub
Private Sub cmdReferenceLoads_Click()
   ' Open reference load entry form
   frmReferenceLoad.Show
End Sub
Private Sub cmdUpdateall_Click()
If txtRequiredFuelRate.Text = vbNullString Then
      MsgBox "Please Enter Fuel Data", vbOKOnly, "Fuel Data Required"
      Me.Enabled = False
      frmFuelArrival.Show
      Exit Sub
End If
'---------------------------------------------------------------------------------------------------------
'Save Load data into the database
   dataLoadData.Refresh
   LoadTime = Text2.Text
   With dataLoadData.Recordset
      .FindFirst ("Date LIKE '*" & CDate(Text1.Text) & "*' AND Time LIKE '*" &
CDbl(Text2.Text) & "*'")
      If .NoMatch = True Then
         .AddNew
         .Fields("Date") = CDate(Text1.Text)
         .Fields("Time") = CDbl(Text2.Text)
         .Fields("Load") = CDbl(Text3.Text)
         .Fields("GenOnLoad") = CDbl(cboGenOnLoad.Text)
         .Update
         txtPresentFuelRate.Text = PresentRate(CDbl(Text3.Text), CDbl(cboGenOnLoad.Text))
```

```
    Else
      checkdata = MsgBox("Data already exist. Over-write?", vbYesNo, "Existing Date and
Time")
      If checkdata = vbYes Then
        .Edit
        .Fields("Date") = CDate(Text1.Text)
        .Fields("Time") = CDbl(Text2.Text)
        .Fields("Load") = CDbl(Text3.Text)
        .Fields("GenOnLoad") = CDbl(cboGenOnLoad.Text)
        .Update
        txtPresentFuelRate.Text = PresentRate(CDbl(Text3.Text),
CDbl(cboGenOnLoad.Text))
      Else
        Text2.SetFocus
        Exit Sub
      End If
    End If
  End With
'----------------------------------------------------------------------------------
'-------- Enter the Present RFC in to fuel data database ---------------------------
'----------------------------------------------------------------------------------
  With frmFuelArrival.dataStockArrival.Recordset
    .MoveLast
    FSAD = .Fields("NewStockDate")
  End With
  TimeSinceNow = CDbl(DateDiff("h", FSAD, CDate(Text1.Text))) + CDbl(Text2.Text)
 '--------^ Calculates the time diff in hours ------
  With frmFuelArrival.dataRFC.Recordset
    .FindFirst ("Time LIKE '*" & CDbl(TimeSinceNow + 1) & "*'")
    .Edit
    .Fields("PRFC") = txtPresentFuelRate.Text
    .Update
  End With
```

```
'--------------------------------------------------------------------------------
   monthtype = GetMonth(Text1.Text)
'----------^ Get the month type from the FUNCTION -----------
   daytype = GetDay(Text1.Text)
 '---------- ^Get the day type from the FUNCTION -------------
   conlevel = GetConstraintLevel(CDbl(TimeSinceNow))
 '---------- ^Get the Constraint Level from FUNCTION ---------

   FuelGraph

   txtLastHour.Text = txtPresentHour.Text
   txtPresentHour.Text = Text3.Text
   DUF = GetDUF(conlevel, LoadTime, CDbl(Text3.Text))
 '------- ^Get the value of DUF --------------
'--------------------------------------------------------------------------------
'------------------- Enter the DUF values in to matrix -------------------
'--------------------------------------------------------------------------------
      LCVAL = CDbl(Text3.Text)
      LTime = CDbl(LoadTime + 1)
      alpha = 4
      beta = 5
      gamma = 6
      With frmReferenceLoad.dataBaseLoads.Recordset
         .FindFirst ("Time LIKE '*" & LTime & "*'")
         ln = .Fields("NL")
         lm = .Fields("MCL")
         ls = .Fields("SCL")
      End With

      If LCVAL > ln Then
         With frmDUFMatrix.dataDUFmatrix.Recordset
            .FindFirst ("DUFvar LIKE '*" & CDbl(alpha & conlevel & monthtype & daytype &
LTime) & "*'")
```

```
If .NoMatch = True Then
  .AddNew
  .Fields("DUFvar") = CDbl(alpha & conlevel & monthtype & daytype & LTime)
  .Fields("DUFvalue") = CDbl((.Fields("DUFvalue") + ((LCVAL - lm) / (ln - lm))) / 2)
  .Update
Else
  .Edit
  .Fields("DUFvar") = CDbl(alpha & conlevel & monthtype & daytype & LTime)
  .Fields("DUFvalue") = CDbl((.Fields("DUFvalue") + ((LCVAL - lm) / (ln - lm))) / 2)
  .Update
End If

    .FindFirst ("DUFvar LIKE '*" & CDbl(beta & conlevel & monthtype & daytype &
LTime) & "*'")
    If .NoMatch = True Then
      .AddNew
      .Fields("DUFvar") = CDbl(beta & conlevel & monthtype & daytype & LTime)
      .Fields("DUFvalue") = 1
      .Update
    Else
      .Edit
      .Fields("DUFvar") = CDbl(beta & conlevel & monthtype & daytype & LTime)
      .Fields("DUFvalue") = 1
      .Update
    End If

.FindFirst ("DUFvar LIKE '*" & CDbl(gamma & conlevel & monthtype & daytype &
LTime) & "*'")
If .NoMatch = True Then
  .AddNew
  .Fields("DUFvar") = CDbl(gamma & conlevel & monthtype & daytype & LTime)
  .Fields("DUFvalue") = 1
  .Update
```

```
            Else
               .Edit
               .Fields("DUFvar") = CDbl(gamma & conlevel & monthtype & daytype & LTime)
               .Fields("DUFvalue") = 1
               .Update
            End If

         End With
      End If

      If LCVAL < ln And LCVAL > lm Then
         With frmDUFMatrix.dataDUFmatrix.Recordset
            .FindFirst ("DUFvar LIKE '*" & CDbl(alpha & conlevel & monthtype & daytype & 
LTime) & "*'")
            If .NoMatch = True Then
               .AddNew
               .Fields("DUFvar") = CDbl(alpha & conlevel & monthtype & daytype & LTime)
               .Fields("DUFvalue") = CDbl((.Fields("DUFvalue") + ((LCVAL - lm) / (ln - lm))) / 2)
               .Update
            Else
               .Edit
               .Fields("DUFvar") = CDbl(alpha & conlevel & monthtype & daytype & LTime)
               .Fields("DUFvalue") = CDbl((.Fields("DUFvalue") + ((LCVAL - lm) / (ln - lm))) / 2)
               .Update
            End If

                .FindFirst ("DUFvar LIKE '*" & CDbl(beta & conlevel & monthtype & daytype & 
LTime) & "*'")
                If .NoMatch = True Then
                   .AddNew
                   .Fields("DUFvar") = CDbl(beta & conlevel & monthtype & daytype & LTime)
                   .Fields("DUFvalue") = 1
                   .Update
```

```
            Else
              .Edit
              .Fields("DUFvar") = CDbl(beta & conlevel & monthtype & daytype & LTime)
              .Fields("DUFvalue") = 1
              .Update
            End If

        .FindFirst ("DUFvar LIKE '*" & CDbl(gamma & conlevel & monthtype & daytype &
LTime) & "*'")
        If .NoMatch = True Then
          .AddNew
          .Fields("DUFvar") = CDbl(gamma & conlevel & monthtype & daytype & LTime)
          .Fields("DUFvalue") = 1
          .Update
        Else
          .Edit
          .Fields("DUFvar") = CDbl(gamma & conlevel & monthtype & daytype & LTime)
          .Fields("DUFvalue") = 1
          .Update
        End If
      End With
    End If
    If LCVAL = ln Then
      With frmDUFMatrix.dataDUFmatrix.Recordset
        .FindFirst ("DUFvar LIKE '*" & CDbl(alpha & conlevel & monthtype & daytype &
LTime) & "*'")
        If .NoMatch = True Then
          .AddNew
          .Fields("DUFvar") = CDbl(alpha & conlevel & monthtype & daytype & LTime)
          .Fields("DUFvalue") = 1
          .Update
        Else
          .Edit
```

```
        .Fields("DUFvar") = CDbl(alpha & conlevel & monthtype & daytype & LTime)
        .Fields("DUFvalue") = 1
        .Update
    End If

            .FindFirst ("DUFvar LIKE '*" & CDbl(beta & conlevel & monthtype & daytype &
LTime) & "*'")
            If .NoMatch = True Then
                .AddNew
                .Fields("DUFvar") = CDbl(beta & conlevel & monthtype & daytype & LTime)
                .Fields("DUFvalue") = 1
                .Update
            Else
                .Edit
                .Fields("DUFvar") = CDbl(beta & conlevel & monthtype & daytype & LTime)
                .Fields("DUFvalue") = 1
                .Update
            End If

    .FindFirst ("DUFvar LIKE '*" & CDbl(gamma & conlevel & monthtype & daytype &
LTime) & "*'")
    If .NoMatch = True Then
        .AddNew
        .Fields("DUFvar") = CDbl(gamma & conlevel & monthtype & daytype & LTime)
        .Fields("DUFvalue") = 1
        .Update
    Else
        .Edit
        .Fields("DUFvar") = CDbl(gamma & conlevel & monthtype & daytype & LTime)
        .Fields("DUFvalue") = 1
        .Update
    End If
  End With
```

```
End If

If LCVAL = lm Then
   With frmDUFMatrix.dataDUFmatrix.Recordset
      .FindFirst ("DUFvar LIKE '*" & CDbl(alpha & conlevel & monthtype & daytype &
LTime) & "*'")
      If .NoMatch = True Then
         .AddNew
         .Fields("DUFvar") = CDbl(alpha & conlevel & monthtype & daytype & LTime)
         .Fields("DUFvalue") = 0
         .Update
      Else
         .Edit
         .Fields("DUFvar") = CDbl(alpha & conlevel & monthtype & daytype & LTime)
         .Fields("DUFvalue") = 0
         .Update
      End If

         .FindFirst ("DUFvar LIKE '*" & CDbl(beta & conlevel & monthtype & daytype &
LTime) & "*'")
         If .NoMatch = True Then
            .AddNew
            .Fields("DUFvar") = CDbl(beta & conlevel & monthtype & daytype & LTime)
            .Fields("DUFvalue") = 1
            .Update
         Else
            .Edit
            .Fields("DUFvar") = CDbl(beta & conlevel & monthtype & daytype & LTime)
            .Fields("DUFvalue") = 1
            .Update
         End If

      .FindFirst ("DUFvar LIKE '*" & CDbl(gamma & conlevel & monthtype & daytype &
```

```
LTime) & "*'")
            If .NoMatch = True Then
               .AddNew
               .Fields("DUFvar") = CDbl(gamma & conlevel & monthtype & daytype & LTime)
               .Fields("DUFvalue") = 1
               .Update
            Else
               .Edit
               .Fields("DUFvar") = CDbl(gamma & conlevel & monthtype & daytype & LTime)
               .Fields("DUFvalue") = 1
               .Update
            End If
         End With
      End If

      If LCVAL < lm And LCVAL > ls Then
         With frmDUFMatrix.dataDUFmatrix.Recordset
            .FindFirst ("DUFvar LIKE '*" & CDbl(alpha & conlevel & monthtype & daytype &
LTime) & "*'")
            If .NoMatch = True Then
               .AddNew
               .Fields("DUFvar") = CDbl(alpha & conlevel & monthtype & daytype & LTime)
               .Fields("DUFvalue") = 0
               .Update
            Else
               .Edit
               .Fields("DUFvar") = CDbl(alpha & conlevel & monthtype & daytype & LTime)
               .Fields("DUFvalue") = 0
               .Update
            End If

                  .FindFirst ("DUFvar LIKE '*" & CDbl(beta & conlevel & monthtype & daytype &
LTime) & "*'")
```

```
                If .NoMatch = True Then
                    .AddNew
                    .Fields("DUFvar") = CDbl(beta & conlevel & monthtype & daytype & LTime)
                    .Fields("DUFvalue") = CDbl((.Fields("DUFvalue") + ((LCVAL - ls) / (lm - ls))) / 2)
                    .Update
                Else
                    .Edit
                    .Fields("DUFvar") = CDbl(beta & conlevel & monthtype & daytype & LTime)
                    .Fields("DUFvalue") = CDbl((.Fields("DUFvalue") + ((LCVAL - ls) / (lm - ls))) / 2)
                    .Update
                End If

            .FindFirst ("DUFvar LIKE '*" & CDbl(gamma & conlevel & monthtype & daytype &
LTime) & "*'")
            If .NoMatch = True Then
                .AddNew
                .Fields("DUFvar") = CDbl(gamma & conlevel & monthtype & daytype & LTime)
                .Fields("DUFvalue") = 1
                .Update
            Else
                .Edit
                .Fields("DUFvar") = CDbl(gamma & conlevel & monthtype & daytype & LTime)
                .Fields("DUFvalue") = 1
                .Update
            End If
        End With
    End If

    If LCVAL = ls Then
        With frmDUFMatrix.dataDUFmatrix.Recordset
            .FindFirst ("DUFvar LIKE '*" & CDbl(alpha & conlevel & monthtype & daytype &
LTime) & "*'")
            If .NoMatch = True Then
```

```
    .AddNew
    .Fields("DUFvar") = CDbl(alpha & conlevel & monthtype & daytype & LTime)
    .Fields("DUFvalue") = 0
    .Update
  Else
    .Edit
    .Fields("DUFvar") = CDbl(alpha & conlevel & monthtype & daytype & LTime)
    .Fields("DUFvalue") = 0
    .Update
  End If

      .FindFirst ("DUFvar LIKE '*" & CDbl(beta & conlevel & monthtype & daytype &
LTime) & "*'")
      If .NoMatch = True Then
        .AddNew
        .Fields("DUFvar") = CDbl(beta & conlevel & monthtype & daytype & LTime)
        .Fields("DUFvalue") = 0
        .Update
      Else
        .Edit
        .Fields("DUFvar") = CDbl(beta & conlevel & monthtype & daytype & LTime)
        .Fields("DUFvalue") = 0
        .Update
      End If

  .FindFirst ("DUFvar LIKE '*" & CDbl(gamma & conlevel & monthtype & daytype &
LTime) & "*'")
  If .NoMatch = True Then
    .AddNew
    .Fields("DUFvar") = CDbl(gamma & conlevel & monthtype & daytype & LTime)
    .Fields("DUFvalue") = 1
    .Update
  Else
```

```
            .Edit
            .Fields("DUFvar") = CDbl(gamma & conlevel & monthtype & daytype & LTime)
            .Fields("DUFvalue") = 1
            .Update
         End If
      End With
   End If

   If LCVAL < ls Then
      With frmDUFMatrix.dataDUFmatrix.Recordset
         .FindFirst ("DUFvar LIKE '*" & CDbl(alpha & conlevel & monthtype & daytype &
LTime) & "*'")
         If .NoMatch = True Then
            .AddNew
            .Fields("DUFvar") = CDbl(alpha & conlevel & monthtype & daytype & LTime)
            .Fields("DUFvalue") = 0
            .Update
         Else
            .Edit
            .Fields("DUFvar") = CDbl(alpha & conlevel & monthtype & daytype & LTime)
            .Fields("DUFvalue") = 0
            .Update
         End If

               .FindFirst ("DUFvar LIKE '*" & CDbl(beta & conlevel & monthtype & daytype &
LTime) & "*'")
               If .NoMatch = True Then
                  .AddNew
                  .Fields("DUFvar") = CDbl(beta & conlevel & monthtype & daytype & LTime)
                  .Fields("DUFvalue") = 0
                  .Update
               Else
                  .Edit
```

```
                .Fields("DUFvar") = CDbl(beta & conlevel & monthtype & daytype & LTime)
                .Fields("DUFvalue") = 0
                .Update
            End If

        .FindFirst ("DUFvar LIKE '*" & CDbl(gamma & conlevel & monthtype & daytype &
LTime) & "*'")
        If .NoMatch = True Then
          .AddNew
          .Fields("DUFvar") = CDbl(gamma & conlevel & monthtype & daytype & LTime)
          .Fields("DUFvalue") = CDbl((.Fields("DUFvalue") + (LCVAL / ls)) / 2)
          .Update
        Else
          .Edit
          .Fields("DUFvar") = CDbl(gamma & conlevel & monthtype & daytype & LTime)
          .Fields("DUFvalue") = CDbl((.Fields("DUFvalue") + (LCVAL / ls)) / 2)
          .Update
        End If
      End With
    End If

  ClearText     '---- Call sub routine to clear the texts ----
  picLoad_Click
txtForecastLoad.Text = CInt(ForecastLoad(LoadTime, conlevel, monthtype, daytype))
End Sub

Private Sub Command3_Click()
  frmFuelArrival.Show
End Sub

Private Sub Form_Load()
'-------------------------------------------------------------------------------------------
'----------------------- setting initial conditions and the public variables ------
```

```
'--------------------------------------------------------------------------------------------
  chktol = 0
  chktolasone = 1
  chksevere = 0

  txtCheckDate.Text = Format$(Now, "mm/dd/yyyy")
'--------------------------------------------------------------------------------------------
  lblNormal.FontBold = True              '-------- Set initial constraint level to -------
  lblNormal.FontUnderline = True
  lblNormal.FontSize = 10
  picConstraintColour1.BackColor = vbGreen    '----------------- NORMAL ---------------------
'------------------------------------------------------------------------------------------------------------------
'Populate the Load graph with the reference load curves
  Dim dataval()
  dataLoadData.Refresh                            '---- Refresh both ----
  frmReferenceLoad.dataBaseLoads.Refresh          '----- Databases ------

  With frmReferenceLoad.dataBaseLoads.Recordset  '---- Check for number of records
enterd for Load ----
    .MoveLast
    rcount = .RecordCount
    ReDim dataval(1 To rcount, 1 To 4)          '---- and declare the array variable ----
  End With
    frmReferenceLoad.dataBaseLoads.Recordset.MoveFirst
    For i = 1 To rcount
      dataval(i, 2) = frmReferenceLoad.dataBaseLoads.Recordset.Fields("NL")
      dataval(i, 3) = frmReferenceLoad.dataBaseLoads.Recordset.Fields("MCL")
      dataval(i, 4) = frmReferenceLoad.dataBaseLoads.Recordset.Fields("SCL")
      frmReferenceLoad.dataBaseLoads.Recordset.MoveNext
    Next i

  With dataLoadData.Recordset
    If .RecordCount <> 0 Then
```

```
  .MoveFirst
  Do While .EOF = False
    If .Fields("Date") = CDate(txtCheckDate.Text) Then
      Placement = CDbl(.Fields("Time")) + 1
      dataval(Placement, 1) = .Fields("Load")
    End If
    .MoveNext
  Loop
  End If
End With

With chartLoadData
  With .Plot.Axis(VtChAxisIdX)
    .AxisTitle.Text = "Time (hrs)"
    .ValueScale.Auto = True
    .ValueScale.Maximum = rcount
    .ValueScale.Minimum = 1
    .CategoryScale.LabelTick = True
  End With
  With .Plot.Axis(VtChAxisIdY)
    .AxisTitle.Text = "Load (kW)"
    .AxisTitle.TextLayout.VertAlignment = VtVerticalAlignmentCenter
    .AxisTitle.TextLayout.Orientation = VtOrientationUp
    .ValueScale.Auto = True
    .CategoryScale.LabelTick = True
  End With
End With

With chartLoadData
  .RowCount = 4
  .ColumnCount = rcount
  .ChartData = dataval
```

```
            For c = 1 To rcount
                rowLabl = c - 1
                .DataGrid.RowLabel(c, 1) = rowLabl
            Next c
        .Plot.SeriesCollection(2).LegendText = "NL"
        .Plot.SeriesCollection(3).LegendText = "MCL"
        .Plot.SeriesCollection(4).LegendText = "SCL"
        .Plot.SeriesCollection(1).LegendText = "Present"
        .Legend.Location.LocationType = VtChLocationTypeBottom
    End With
'Load curve has been populated with the reference load curves
'------------------------------------------------------------------------------------------------------------------
'------------------------------------------------------------------------------------------------------------------
'Populate the available generator details
    frmNewGenerator.dataAvailableGensets.Refresh
    With frmNewGenerator.dataAvailableGensets.Recordset
        If .RecordCount <> 0 Then
            Do While .EOF = False
                Select Case .Fields("GenNumber")
                    Case "1"
                        txtGen1Cap.Text = .Fields("RatedCapacity")
                        txtGen1Model.Text = .Fields("GenName")
                        cboGenOnLoad.AddItem "1"
                    Case "2"
                        txtGen2Cap.Text = .Fields("RatedCapacity")
                        txtGen2Model.Text = .Fields("GenName")
                        cboGenOnLoad.AddItem "2"
                    Case "3"
                        txtGen3Cap.Text = .Fields("RatedCapacity")
                        TxtGen3Model.Text = .Fields("GenName")
                        cboGenOnLoad.AddItem "3"
                    Case "4"
```

```
            txtGen4Cap.Text = .Fields("RatedCapacity")
            txtGen4Model.Text = .Fields("GenName")
            cboGenOnLoad.AddItem "4"
          Case "5"
            txtGen5Cap.Text = .Fields("RatedCapacity")
            txtGen5Model.Text = .Fields("GenName")
            cboGenOnLoad.AddItem "5"
          Case "6"
            txtGen6Cap.Text = .Fields("RatedCapacity")
            txtGen6Model.Text = .Fields("GenName")
            cboGenOnLoad.AddItem "6"
        End Select
      .MoveNext
      Loop
    End If
  End With

'End of generator details populating
'-------------------------------------------------------------------------------------------------------------------
End Sub

Private Sub Option4_Click()
  picConstraintColour2.BackColor = vbGreen
End Sub

Private Sub Option5_Click()
  picConstraintColour2.BackColor = vbYellow
End Sub

Private Sub Option6_Click()
  picConstraintColour2.BackColor = vbRed
End Sub
```

```
Private Sub picLoad_Click()
  Dim dataval()
  dataLoadData.Refresh                          '---- Refresh both ----
  frmReferenceLoad.dataBaseLoads.Refresh        '----- Databases ------


  With frmReferenceLoad.dataBaseLoads.Recordset   '---- Check for number of records
enterd for Load ----
    .MoveLast
    ct = .RecordCount
    ReDim dataval(1 To ct, 1 To 4)        '---- and declare the array variable ----
  End With

    frmReferenceLoad.dataBaseLoads.Recordset.MoveFirst
    For i = 1 To ct
      dataval(i, 2) = frmReferenceLoad.dataBaseLoads.Recordset.Fields("NL")
      dataval(i, 3) = frmReferenceLoad.dataBaseLoads.Recordset.Fields("MCL")
      dataval(i, 4) = frmReferenceLoad.dataBaseLoads.Recordset.Fields("SCL")
      frmReferenceLoad.dataBaseLoads.Recordset.MoveNext
    Next i

  With dataLoadData.Recordset
    If .RecordCount <> 0 Then
    .MoveFirst
    Do While .EOF = False
      If .Fields("Date") = CDate(txtCheckDate.Text) Then
        Placement = CDbl(.Fields("Time")) + 1
        dataval(Placement, 1) = .Fields("Load")
      End If
      .MoveNext
    Loop
    End If
```

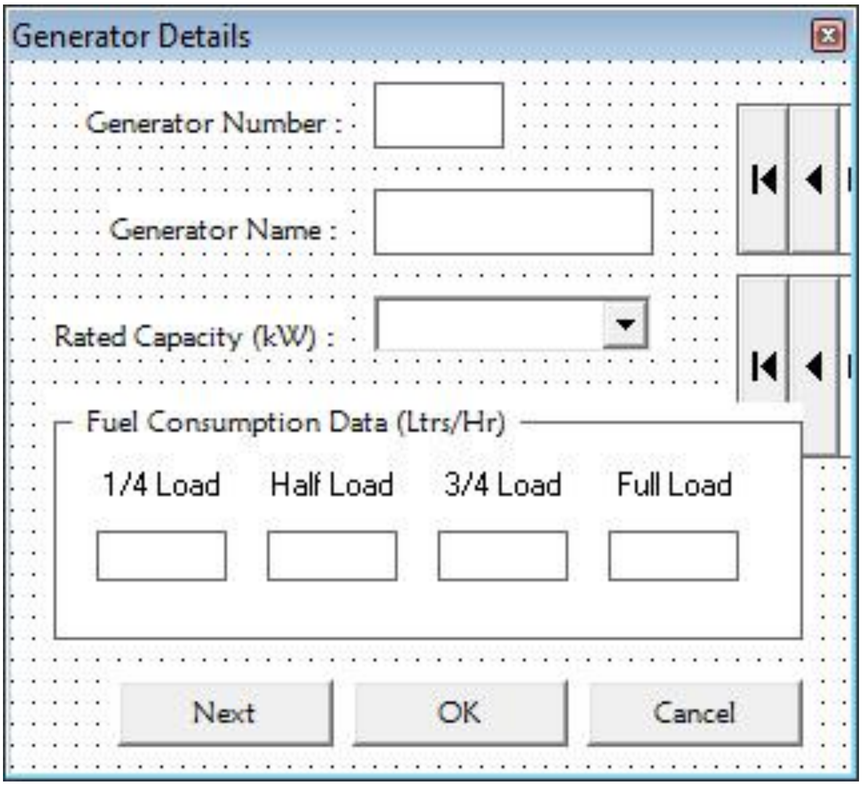
```
End With

With chartLoadData
    With .Plot.Axis(VtChAxisIdX)
        .AxisTitle.Text = "Time (hrs)"
        .ValueScale.Auto = True
        .ValueScale.Maximum = ct
        .ValueScale.Minimum = 1
        .CategoryScale.LabelTick = True
    End With
    With .Plot.Axis(VtChAxisIdY)
        .AxisTitle.Text = "Load (kW)"
        .AxisTitle.TextLayout.VertAlignment = VtVerticalAlignmentCenter
        .AxisTitle.TextLayout.Orientation = VtOrientationUp
        .ValueScale.Auto = True
        .CategoryScale.LabelTick = True
    End With
End With

With chartLoadData
    .RowCount = 4
    .ColumnCount = ct
    .ChartData = dataval
        For c = 1 To ct
            rowLabl = c - 1
            .DataGrid.RowLabel(c, 1) = rowLabl
        Next c
    .Plot.SeriesCollection(2).LegendText = "NL"
    .Plot.SeriesCollection(3).LegendText = "MCL"
    .Plot.SeriesCollection(4).LegendText = "SCL"
    .Plot.SeriesCollection(1).LegendText = "Present"
    .Legend.Location.LocationType = VtChLocationTypeBottom
```

```
    End With
End Sub

Private Sub Text1_Click()
    'Load calender to enter the date
    frmCalender.Show
    'Save the calender caller
    frmCalender.caller.Text = "Text1.Text"
End Sub

Private Sub Text31_Click()
    'Load calender to enter the date
    frmCalender.Show
    'Save the calender caller
    frmCalender.caller.Text = "Text31.Text"
End Sub

Private Sub Text34_Click()
    'Load calender to enter the date
    frmCalender.Show
    'Save the calender caller
    frmCalender.caller.Text = "Text34.Text"
End Sub

Private Sub FuelGraph()
'-------------------------------------------------------------------------------------
'----------------- Fuel Graph --------------------------------------------------
'-------------------------------------------------------------------------------------
    Dim fuelval()
        With frmFuelArrival.dataStockArrival.Recordset
        .MoveLast
        FSAD = .Fields("NewStockDate")
```

```
    End With
  fueltime = CDbl(DateDiff("h", FSAD, CDate(Text1.Text))) + CDbl(frmMain.LoadTime) + 1
'-------- ^Calculates the time diff in hours ------
  frmFuelArrival.dataRFC.Refresh
    ReDim fuelval(1 To 24, 1 To 3)        '---- and declare the array variable ----
  If fueltime < 13 Then
    starttime = 1
  Else
    starttime = fueltime - 12
  End If
  endtime = starttime + 24
    frmFuelArrival.dataRFC.Recordset.MoveFirst
    If starttime > 1 Then
      For c = 1 To starttime - 1
        frmFuelArrival.dataRFC.Recordset.MoveNext
      Next c
    End If

    For i = 1 To 24
      fuelval(i, 2) = frmFuelArrival.dataRFC.Recordset.Fields("PosTol")
      fuelval(i, 3) = frmFuelArrival.dataRFC.Recordset.Fields("NegTol")
      fuelval(i, 1) = frmFuelArrival.dataRFC.Recordset.Fields("FRFC")
      frmFuelArrival.dataRFC.Recordset.MoveNext
    Next i

  With frmMain.chartFuelData
    With .Plot.Axis(VtChAxisIdX)
      .AxisTitle.Text = "Time (hrs)"
      .ValueScale.Auto = Auto
      .ValueScale.Maximum = endtime
      .ValueScale.Minimum = starttime
      .CategoryScale.LabelTick = True
    End With
```

```
        With .Plot.Axis(VtChAxisIdY)
            .AxisTitle.Text = "RFC (Liters)"
            .AxisTitle.TextLayout.VertAlignment = VtVerticalAlignmentCenter
            .AxisTitle.TextLayout.Orientation = VtOrientationUp
            .ValueScale.Auto = True
            .CategoryScale.LabelTick = True
        End With
    End With

    With frmMain.chartFuelData
        .RowCount = 3
        .ColumnCount = 24
        .ChartData = fuelval
            For c = 1 To 24
                rowLabl = starttime - 1
                .DataGrid.RowLabel(c, 1) = rowLabl
                starttime = starttime + 1
                If starttime = 25 Then
                    starttime = 1
                End If
            Next c
        .Plot.SeriesCollection(2).LegendText = "PosTol"
        .Plot.SeriesCollection(3).LegendText = "NegTol"
        .Plot.SeriesCollection(1).LegendText = "Present Rate"
        .Legend.Location.LocationType = VtChLocationTypeBottom
    End With
End Sub

Private Sub ClearText()
    Text3.Text = vbNullString
    Text2.Text = vbNullString
End Sub
```

FORM TO ENTER GENERATOR DETAILS



VISUAL BASIC CODE FOR THE ABOVE FORM

```
Dim db As Database

Dim rs As Recordset

Private Sub btnCancel_Click()
   ClearText
   'close all and exit this form
   Close All
   Unload Me
End Sub

Private Sub btnNext_Click()
      Select Case CDbl(txtGenNumber.Text)
         Case 1
            frmMain.txtGen1Cap.Text = cboRatedCapacity.Text
```

```
            frmMain.txtGen1Model.Text = txtGenName.Text
            frmMain.cboGenOnLoad.AddItem "1"
        Case 2
            frmMain.txtGen2Cap.Text = cboRatedCapacity.Text
            frmMain.txtGen2Model.Text = txtGenName.Text
            frmMain.cboGenOnLoad.AddItem "2"
        Case 3
            frmMain.txtGen3Cap.Text = cboRatedCapacity.Text
            frmMain.TxtGen3Model.Text = txtGenName.Text
            frmMain.cboGenOnLoad.AddItem "3"
        Case 4
            frmMain.txtGen4Cap.Text = cboRatedCapacity.Text
            frmMain.txtGen4Model.Text = txtGenName.Text
            frmMain.cboGenOnLoad.AddItem "4"
        Case 5
            frmMain.txtGen5Cap.Text = cboRatedCapacity.Text
            frmMain.txtGen5Model.Text = txtGenName.Text
            frmMain.cboGenOnLoad.AddItem "5"
        Case 6
            frmMain.txtGen6Cap.Text = cboRatedCapacity.Text
            frmMain.txtGen6Model.Text = txtGenName.Text
            frmMain.cboGenOnLoad.AddItem "6"
    End Select
With dataAvailableGensets.Recordset
    .FindFirst ("GenNumber LIKE '*" & CDbl(txtGenNumber.Text) & "*'")
    If .NoMatch = True Then
        .AddNew
            .Fields("GenNumber") = CDbl(txtGenNumber.Text)
            .Fields("GenName") = txtGenName.Text
            .Fields("RatedCapacity") = CDbl(cboRatedCapacity.Text)
            .Fields("FuelQL") = CDbl(txtFuel1.Text)
            .Fields("FuelHL") = CDbl(txtFuel2.Text)
```

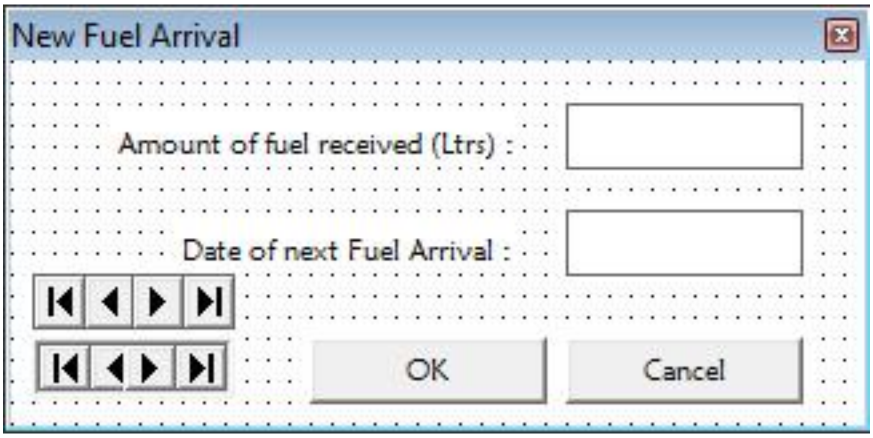
```
            .Fields("FuelTL") = CDbl(txtFuel3.Text)
            .Fields("FuelFL") = CDbl(txtFuel4.Text)
        .Update
    Else
        .Edit
            .Fields("GenNumber") = CDbl(txtGenNumber.Text)
            .Fields("GenName") = txtGenName.Text
            .Fields("RatedCapacity") = CDbl(cboRatedCapacity.Text)
            .Fields("FuelQL") = CDbl(txtFuel1.Text)
            .Fields("FuelHL") = CDbl(txtFuel2.Text)
            .Fields("FuelTL") = CDbl(txtFuel3.Text)
            .Fields("FuelFL") = CDbl(txtFuel4.Text)
        .Update
    End If
  End With
  ClearText
End Sub

Private Sub btnOK_Click()
  If txtGenNumber.Text <> vbNullString Then
    Select Case CDbl(txtGenNumber.Text)
        Case 1
            frmMain.txtGen1Cap.Text = cboRatedCapacity.Text
            frmMain.txtGen1Model.Text = txtGenName.Text
            frmMain.cboGenOnLoad.AddItem "1"
        Case 2
            frmMain.txtGen2Cap.Text = cboRatedCapacity.Text
            frmMain.txtGen2Model.Text = txtGenName.Text
            frmMain.cboGenOnLoad.AddItem "2"
        Case 3
            frmMain.txtGen3Cap.Text = cboRatedCapacity.Text
            frmMain.TxtGen3Model.Text = txtGenName.Text
            frmMain.cboGenOnLoad.AddItem "3"
```

```
        Case 4
          frmMain.txtGen4Cap.Text = cboRatedCapacity.Text
          frmMain.txtGen4Model.Text = txtGenName.Text
          frmMain.cboGenOnLoad.AddItem "4"
        Case 5
          frmMain.txtGen5Cap.Text = cboRatedCapacity.Text
          frmMain.txtGen5Model.Text = txtGenName.Text
          frmMain.cboGenOnLoad.AddItem "5"
        Case 6
          frmMain.txtGen6Cap.Text = cboRatedCapacity.Text
          frmMain.txtGen6Model.Text = txtGenName.Text
          frmMain.cboGenOnLoad.AddItem "6"
      End Select
    With dataAvailableGensets.Recordset
      .FindFirst ("GenNumber LIKE '*" & CDbl(txtGenNumber.Text) & "*'")
      If .NoMatch = True Then
        .AddNew
          .Fields("GenNumber") = CDbl(txtGenNumber.Text)
          .Fields("GenName") = txtGenName.Text
          .Fields("RatedCapacity") = CDbl(cboRatedCapacity.Text)
          .Fields("FuelQL") = CDbl(txtFuel1.Text)
          .Fields("FuelHL") = CDbl(txtFuel2.Text)
          .Fields("FuelTL") = CDbl(txtFuel3.Text)
          .Fields("FuelFL") = CDbl(txtFuel4.Text)
        .Update
      Else
        .Edit
          .Fields("GenNumber") = CDbl(txtGenNumber.Text)
          .Fields("GenName") = txtGenName.Text
          .Fields("RatedCapacity") = CDbl(cboRatedCapacity.Text)
          .Fields("FuelQL") = CDbl(txtFuel1.Text)
          .Fields("FuelHL") = CDbl(txtFuel2.Text)
```

```
            .Fields("FuelTL") = CDbl(txtFuel3.Text)
            .Fields("FuelFL") = CDbl(txtFuel4.Text)
         .Update
      End If
   End With
   End If
   ClearText
      Me.Hide
      frmMain.Enabled = True
      frmMain.SetFocus
End Sub

Private Sub ClearText()
   txtGenNumber.Text = vbNullString
   txtGenName.Text = vbNullString
   cboRatedCapacity.Text = vbNullString
   txtFuel1.Text = vbNullString
   txtFuel2.Text = vbNullString
   txtFuel3.Text = vbNullString
   txtFuel4.Text = vbNullString
   txtGenNumber.SetFocus
End Sub

Private Sub cboRatedCapacity_Click()
   With dataGeneratorList.Recordset
      .FindFirst ("RatedCapacity LIKE '*" & cboRatedCapacity.Text & "*'")
      txtFuel1.Text = .Fields("QuarterLoad")
      txtFuel2.Text = .Fields("HalfLoad")
      txtFuel3.Text = .Fields("ThirdLoad")
      txtFuel4.Text = .Fields("FullLoad")
   End With
End Sub
```

```
Private Sub Form_Unload(Cancel As Integer)
   frmMain.Enabled = True
   frmMain.SetFocus
End Sub
```

FORM FOR NEW FUEL ARRIVAL



VISUAL BASIC CODE FOR THE ABOVE FORM

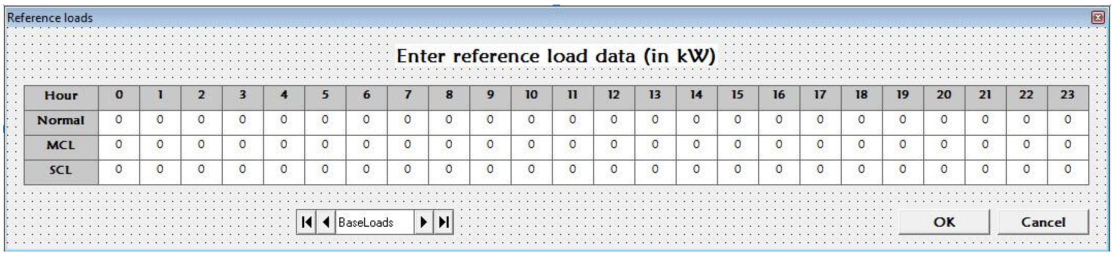
```
Private Sub btnCancel_Click()
    txtFuelAmount.Text = vbNullString
    txtNewStockDate.Text = vbNullString
    Unload Me
    frmMain.Enabled = True
    frmMain.SetFocus
End Sub

Private Sub btnOK_Click()
    If txtFuelAmount.Text = vbNullString Or txtNewStockDate.Text = vbNullString Then
        MsgBox "Please enter the required information", vbOKOnly, "Missing Data"
        Me.SetFocus
    Else
        arrivedate = Format$(Now, "mm/dd/yyyy")
        TimeAvailable = DateDiff("h", arrivedate, CDate(txtNewStockDate.Text))
'-------- ^Calculates the date diff in hours -----------
        rfc = (CDbl(txtFuelAmount.Text) / TimeAvailable)
'-------- ^Calculate Rate of Fuel Consumption rqd ------
```

```
        With dataStockArrival.Recordset
          .AddNew
          .Fields("FuelAmount") = CDbl(txtFuelAmount.Text)
          .Fields("NewStockDate") = Format$(Now, "mm/dd/yyyy")
          .Fields("NextStockDate") = txtNewStockDate.Text
          .Fields("RFC") = rfc
          .Update
        End With
'Enter the fuel details in the main page
      frmMain.txtLastStockAmount.Text = txtFuelAmount.Text
      frmMain.txtNewStockDate.Text = Format$(txtNewStockDate.Text, "dd mmm yyyy")
      frmMain.txtLastStockDate.Text = Format$(Now, "dd mmm yyyy")
      frmMain.txtRequiredFuelRate.Text = Format(rfc, "###0.00")
 '--------- ^Formatted to 2 decimal Places --------------
      Unload Me
      frmMain.Enabled = True
      frmMain.SetFocus
    End If
'---------------------------------------------------------------------------------
'---------------------------- Generate the Fuel Rate  -----------------------
'---------------------------------------------------------------------------------
inc = 0
    With dataRFC.Recordset
      If .EOF = False Then
        .MoveLast
      End If
      If .RecordCount <> 0 Then
        .MoveFirst
        Do While .EOF = False
          .Delete
          .MoveNext
        Loop
```

```
        End If
          For i = 1 To TimeAvailable
            inc = inc + rfc
            .AddNew
            .Fields("Time") = CDbl(i)
            .Fields("PHI") = CDbl(inc)
            .Fields("PosTol") = CDbl((rfc * 2) + inc)
            .Fields("NegTol") = CDbl(inc - (rfc * 2))
            .Update
          Next i
    End With
    FuelGraph
End Sub

Private Sub txtNewStockDate_Click()
    frmCalender.Show
    frmCalender.caller.Text = "FuelArrival"
End Sub

Private Sub FuelGraph()
'-----------------------------------------------------------------------------------
'------------------ Fuel Graph ------------------------------------------------------
'-----------------------------------------------------------------------------------
    Dim fuelval()
    dataRFC.Refresh
        ReDim fuelval(1 To 24, 1 To 3)        '---- and declare the array variable ----
        dataRFC.Recordset.MoveFirst
        For i = 1 To 24
          fuelval(i, 2) = dataRFC.Recordset.Fields("PosTol")
          fuelval(i, 3) = dataRFC.Recordset.Fields("NegTol")
          fuelval(i, 1) = dataRFC.Recordset.Fields("FRFC")
          dataRFC.Recordset.MoveNext
```

```
    Next i
  With frmMain.chartFuelData
    With .Plot.Axis(VtChAxisIdX)
      .AxisTitle.Text = "Time (hrs)"
      .ValueScale.Auto = True
      .ValueScale.Maximum = 24
      .ValueScale.Minimum = 1
      .CategoryScale.LabelTick = True
    End With
    With .Plot.Axis(VtChAxisIdY)
      .AxisTitle.Text = "RFC (Liters)"
      .AxisTitle.TextLayout.VertAlignment = VtVerticalAlignmentCenter
      .AxisTitle.TextLayout.Orientation = VtOrientationUp
      .ValueScale.Auto = True
      .CategoryScale.LabelTick = True
    End With
  End With
  With frmMain.chartFuelData
    .RowCount = 3
    .ColumnCount = 24
    .ChartData = fuelval
      For c = 1 To 24
        rowLabl = c - 1
        .DataGrid.RowLabel(c, 1) = rowLabl
      Next c
    .Plot.SeriesCollection(2).LegendText = "PosTol"
    .Plot.SeriesCollection(3).LegendText = "NegTol"
    .Plot.SeriesCollection(1).LegendText = "Present Rate"
    .Legend.Location.LocationType = VtChLocationTypeBottom
  End With
End Sub
```

FORM TO ENTER THE DETAILS OF THE REFERENCE LOADS



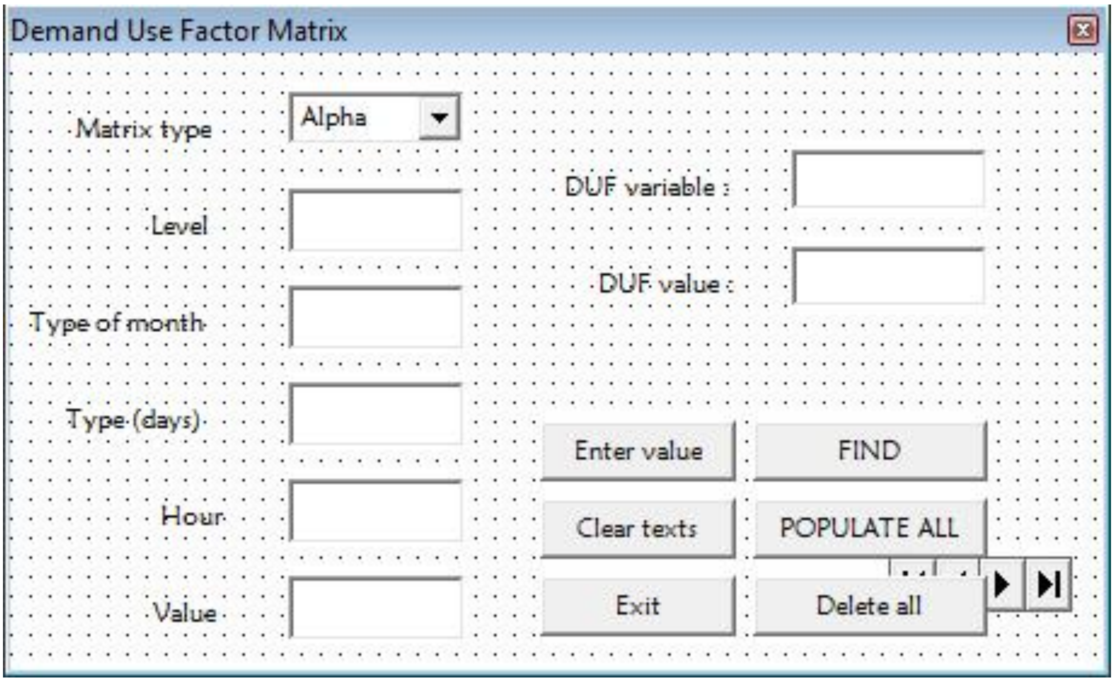
Hour	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
Normal	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
MCL	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
SCL	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

VISUAL BASIC CODE FOR THE ABOVE FORM

```
Private Sub btnCancel_Click()
    Unload Me
    frmMain.Enabled = True
    frmMain.SetFocus
End Sub

Private Sub btnOK_Click()
    With dataBaseLoads.Recordset
        For i = 0 To 23
            .FindFirst ("Time LIKE '*" & CDbl(i + 1) & "*'")
            .Edit
                .Fields("NL") = CDbl(txtNL(i).Text)
                .Fields("MCL") = txtMCL(i).Text
                .Fields("SCL") = txtSCL(i).Text
                .Fields("Time") = i + 1
            .Update
        Next i
    End With

    Unload Me
    frmMain.Enabled = True
```

```
  frmMain.SetFocus
End Sub

Private Sub Form_Load()
  dataBaseLoads.Refresh
  With dataBaseLoads.Recordset
    .MoveFirst
    For i = 0 To 23
        txtNL(i).Text = .Fields("NL")
        txtMCL(i).Text = .Fields("MCL")
        txtSCL(i).Text = .Fields("SCL")
        .MoveNext
    Next i
  End With
End Sub

Private Sub Form_Unload(Cancel As Integer)
  frmMain.Enabled = True
  frmMain.SetFocus
End Sub
```

FORM FOR THE DEMAND USE FACTOR MATRIX MANAGEMENT



VISUAL BASIC CODE FOR THIS FORM

```
Private Sub cmdDeleteAll_Click()
    With dataDUFmatrix.Recordset
        .MoveLast
        ct = .RecordCount
        .MoveFirst
        For i = 1 To ct
            .Delete
            .MoveNext
        Next i
    End With
End Sub

Private Sub cmdFind_Click()
    Select Case cboMatType.Text
```

```
    Case "Alpha"
      MatType = 4
    Case "Beta"
      MatType = 5
    Case "Gamma"
      MatType = 6
  End Select
  Text5.Text = CDbl(MatType) & CDbl(Text1.Text) & CDbl(Text2.Text) & CDbl(Text3.Text) &
CDbl((Text4.Text) + 1)
  Text6.Text = vbNullString
  With dataDUFmatrix.Recordset
    .FindFirst ("DUFvar LIKE '*" & CDbl(Text5.Text) & "*'")
    If .NoMatch = True Then
      MsgBox "No matching data", vbOKOnly, "Find"
    Else
      Text5.Text = .Fields("DUFvar")
      Text7.Text = .Fields("DUFvalue")
    End If
  End With
End Sub

Private Sub cmdPopulate_Click()
  For Mat = 4 To 6
    For level = 1 To 3
      For monthtype = 1 To 4
        For daytype = 1 To 2
          For hr = 1 To 24
              With dataDUFmatrix.Recordset
                .FindFirst ("DUFvar LIKE '*" & CDbl(Mat & level & monthtype & daytype &
hr) & "*'")
                If .NoMatch = True Then
                  .AddNew
                  .Fields("DUFvar") = CDbl(Mat & level & monthtype & daytype & hr)
```

```
                    .Fields("DUFvalue") = 1
                    .Update
                Else
                    .Edit
                    .Fields("DUFvar") = CDbl(Mat & level & monthtype & daytype & hr)
                    .Fields("DUFvalue") = 1
                    .Update
                End If
            End With
        Next hr
      Next daytype
    Next monthtype
  Next level
 Next Mat
End Sub
```

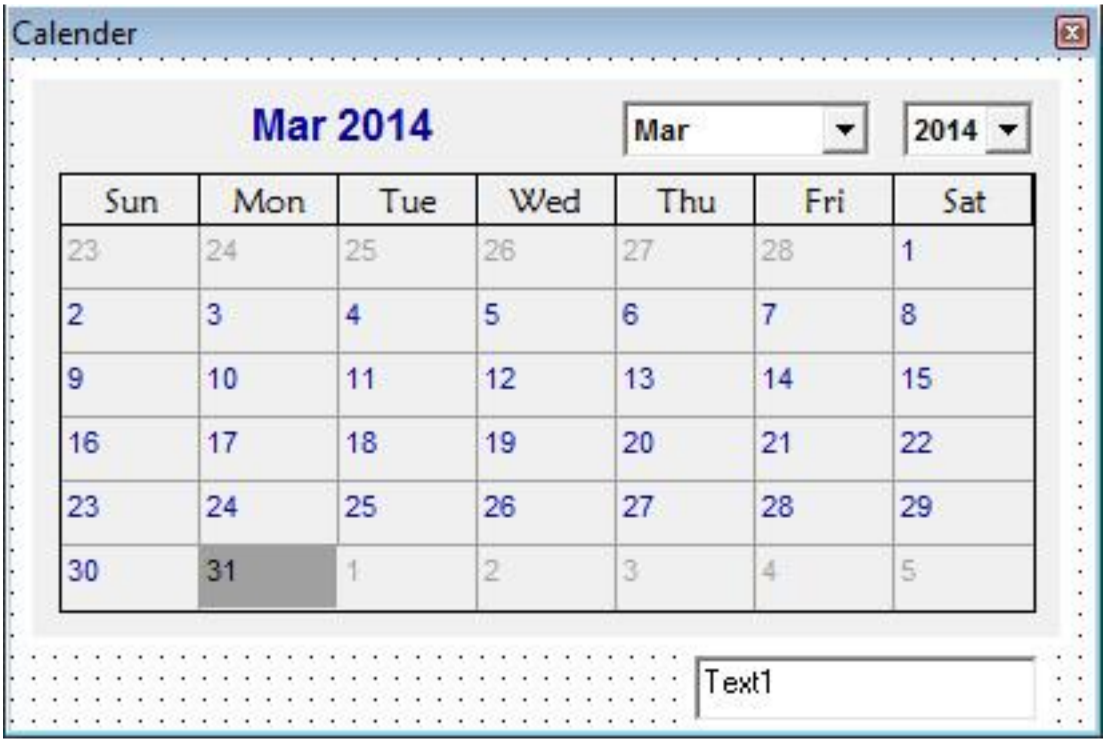
Private Sub Command1_Click()

```
 Select Case cboMatType.Text
   Case "Alpha"
     MatType = 4
   Case "Beta"
     MatType = 5
   Case "Gamma"
     MatType = 6
 End Select
 If Text1.Text = vbNullString Or Text2.Text = vbNullString Or Text3.Text = vbNullString Or
Text4.Text = vbNullString Or Text6.Text = vbNullString Then
   MsgBox "Please enter all the required values", vbOKOnly, "Missing Data"
 Else
   If Text1.Text < 1 Or Text1.Text > 3 Then
     MsgBox "Level should be between 1 and 3", vbOKOnly, "Level out of range"
     Text1.SetFocus
     ElseIf Text2.Text < 1 Or Text2.Text > 4 Then
```

```
            MsgBox "Type of month should be between 1 and 4", vbOKOnly, "Type of Month
out of range"
            Text2.SetFocus
            ElseIf Text3.Text < 1 Or Text3.Text > 2 Then
              MsgBox "Type of day should be between 1 and 2", vbOKOnly, "Type of Day out of
range"
              Text3.SetFocus
              ElseIf Text4.Text < 0 Or Text4.Text > 23 Then
                MsgBox "Hours should be between 1 and 24", vbOKOnly, "Hours out of range"
                Text4.SetFocus
                ElseIf Text6.Text < -1 Or Text6.Text > 1 Then
                  MsgBox "DUF Value should be between -1 and 1", vbOKOnly, "Value out of
range"
                  Text6.SetFocus
    Else
    Text5.Text = CDbl(MatType) & CDbl(Text1.Text) & CDbl(Text2.Text) & CDbl(Text3.Text)
& CDbl((Text4.Text) + 1)
    Text7.Text = CDbl(Text6.Text)
      With dataDUFmatrix.Recordset
        .FindFirst ("DUFvar LIKE '*" & CDbl(Text5.Text) & "*'")
        If .NoMatch = True Then
          .AddNew
          .Fields("DUFvar") = CDbl(Text5.Text)
          .Fields("DUFvalue") = CDbl(Text7.Text)
          .Update
        Else
          .Edit
          .Fields("DUFvar") = CDbl(Text5.Text)
          .Fields("DUFvalue") = CDbl(Text7.Text)
          .Update
        End If
      End With
    End If
  End If
```

```
End Sub

Private Sub Command2_Click()
    Text1.Text = vbNullString
    Text2.Text = vbNullString
    Text3.Text = vbNullString
    Text4.Text = vbNullString
    Text5.Text = vbNullString
    Text6.Text = vbnullsting
    Text7.Text = vbNullString
End Sub

Private Sub Command3_Click()
    Unload Me
    frmMain.Enabled = True
End Sub

Private Sub Form_Unload(Cancel As Integer)
    Unload Me
    frmMain.Enabled = True
End Sub
```

FORM USED TO ENTER THE CALENDER DATES



VISUAL BASIC CODE FOR THE ABOVE FORM

```
Private Sub Calendar1_Click()
    'Update the caller text with the date
    Select Case caller.Text
        Case "Text1.Text"
            frmMain.Text1.Text = Format$(Calendar1.Value, "dd mmm yyyy")
        Case "Text34.Text"
            frmMain.Text34.Text = Format$(Calendar1.Value, "dd mmm yyyy")
        Case "Text31.Text"
            frmMain.Text31.Text = Format$(Calendar1.Value, "dd mmm yyyy")
        Case "FuelArrival"
            frmFuelArrival.txtNewStockDate.Text = Format$(Calendar1.Value, "dd mmm yyyy")
    End Select
    Calendar1.Value = Now
```

```
   Unload Me
End Sub

Private Sub Form_Load()
   Calendar1.Value = Now
End Sub
```

A8. Matlab code for the simulation

```
%Clear all variables in the Workspace
clear all;

%-------------------------------------------------------------------
%Load the three Demand Curves
%-------------------------------------------------------------------

    load Normal.mat;                    %Read Normal Load
    load MCL.mat;                       %Read Medium Constrained Load
    load SCL.mat;                       %Read SeverlyConstrainedLoad

%-------------------------------------------------------------------
%Calculate load differences
%-------------------------------------------------------------------

for c = 1:24

    LN(1,c)=c;
    LN(2,c)=Normal(2,c)-MCL(2,c);       %Generate the Delta-N matrix

    LM(1,c) = c;
    LM(2,c) = MCL(2,c) - SCL(2,c);      %Generate the Delta-M matrix

    LS(1,c) = c;
    LS(2,c) = SCL(2,c);                 %Generate the Delta-S matrix

end

%-------------------------------------------------------------------
%Load DUF matrices
%-------------------------------------------------------------------

    load ('DUFalpha.mat','DUFalpha');
    load ('DUFbeta.mat', 'DUFbeta');
    load ('DUFgama.mat', 'DUFgama');


%-------------------------------------------------------------------
%Get the Required Input from the User for Fuel available in Stock (FA) and
%Time till next Stock Arrival (TSA)
%-------------------------------------------------------------------

FA = input('What is the total amount of Fuel Available in Stock? :');
%Get the value of FA from User
TSAD = input('How many days till the next stock? :');
%Get the Value of TSA in days from User

startdate = today;       %store the system date as the start date
start = datestr(startdate, 1)
startday = datestr(startdate, 7);
startmonth = datestr(startdate, 5);
startweekday = datestr(startdate, 8);

    TSA = TSAD * 24;            %Convert TSA from days to hours
```

```
    PHI = getphival(FA,TSA);            %Get the value of PHI

    inc = 0;        %An incrementer to generate the total PHI value


%---------------------------------------------------------------------
%---------------------------------------------------------------------


%Defining the global variables to be used
global chktol

%---------------------------------------------------------------------
%Calculate the Matrix for PHI and also the Tolerence
%---------------------------------------------------------------------

for c = 1:TSA

    inc = inc + PHI;            %Calculating the new value of inc

    PH(1,c) = c;                %First row of the matrix is for time
    PH(2,c) = inc;      %Second row of the matrix is for the value of total PHI

    PosTol(1,c) = PHI * 5 + inc;
    NegTol(1,c) = inc - PHI * 5;

end


%---------------------------------------------------------------------
%Calculate the Load Forecast for the number of days entered
%---------------------------------------------------------------------

    monthtype = getmonth(startmonth);
    daytype = getday(startweekday);


    FLC(1,1) = 1;
    FLC(2,1) = DUFalpha(1,monthtype,daytype,1)*LN(2,1) +
DUFbeta(1,monthtype,daytype,1)*LM(2,1) +
DUFgama(1,monthtype,daytype,1)*LS(2,1);    %Generate initial Forecast Matrix

    flc = FLC(2,1);
    chktol = 0;
        theta = thetavalue(flc,chktol);       %Call function 'thetavalue'
        FRFC(1,1) = theta;

%---------------------------------------------------------------------
%Defining the initial values for the variables required
%---------------------------------------------------------------------

    chktol = 0;         %A Variable used to check the status of tolerance crossing
    chktolasone = 1;    %A Variable used to check the time, ck stays as 1
    chksevere = 0;      %Variable that checks the time to change to SCD
    hour = 1;           %A variable used as a counter
    FTSA = TSA - 1;
```

```
%-------------------------------------------------------------------
%Generate the forecast load curve (FLC) using DUF matrices
%-------------------------------------------------------------------

forecastLn = 1; % These variables are used
forecastLm = 0; % to generate the statistics
forecastLs = 0; % at the end of the calculations.

for f = 1:FTSA

    ftsa = f+1;
    hour = hour+1;


        rfc = FRFC(1,f);
        postol = PosTol(1,f); negtol = NegTol(1,f);
            ln = Normal(2,hour);
            lm = MCL(2,hour);
            ls = SCL(2,hour);

    %-----------------------------------------------------------------
    %Assign the Constraint Level
    %-----------------------------------------------------------------


        if rfc >= postol  %Check if the Positve Tolerance limit has been reached
            chktol = 1;  %This variable stays as 1 till the graph cross NegTol
                chktolasone = chktolasone + 1;  %Variable that counts how
                                                %long chktol stays as one.
        end

        if rfc < postol
            if rfc > negtol
                chktolasone = 0;
            end
        end

        if rfc < negtol  %Check if the Negative Tolerance limit has been reached
            chktol = 0;  %This variable stays as 0 till the graph cross PosTol
                chksevere = 0;  %Variable that checks the time to change to
                                %Severe Constained Load
        end

        if chktol == 1
            if chktolasone > 2 | chksevere > 6  %Check the condition for
                                                %severe constrained load
                level = 3;
                forecastLs = forecastLs + 1;
            else
                level = 2;
                forecastLm = forecastLm + 1;
            end
            chksevere = chksevere + 1;
        end

        if chktol == 0
```

```
            level = 1;
            forecastLn = forecastLn + 1;
        end

    %------------------------------------------------------------------
    %------------------------------------------------------------------

    %------------------------------------------------------------------
    %Checking for the type of Month and Type of Day
    %------------------------------------------------------------------

    monthtype = getmonth(startmonth);
    daytype = getday(startweekday);


    %------------------------------------------------------------------

    FLC(2,hour) = DUFalpha(level,monthtype,daytype,hour)*LN(2,hour) +
DUFbeta(level,monthtype,daytype,hour)*LM(2,hour) +
DUFgama(level,monthtype,daytype,hour)*LS(2,hour);
        LCVAL = FLC(2,hour);

    theta = thetavalue(LCVAL,chktol);       %Call function 'thetavalue'

    if ftsa <= TSA
        FRFC(1,ftsa) = FRFC(1,f) +  theta;         %Storing the FRFC matrix
    end


if ftsa <= TSA
    ForecastLoad(1,ftsa)=FLC(2,hour);
end

    if hour == 24
        hour = 0;

        startdate = addtodate(startdate, 1, 'day');
        startmonth = datestr(startdate, 5);
        startweekday = datestr(startdate, 8);

    end

end


%--------------------------------------------------------------------
%Reset the Start date for the realtime calculation
%--------------------------------------------------------------------

startdate = today;      %store the system date as the start date
start = datestr(startdate, 1)
startday = datestr(startdate, 7);
startmonth = datestr(startdate, 5);
startweekday = datestr(startdate, 8);
```

```
%-----------------------------------------------------------------------
%Generating initial LC and RFC
%-----------------------------------------------------------------------

low = -0.1; high = 0.1;
randomnumber = low + (high-low)*rand;

    LC(1,1) = 1;
    LC(2,1) = Normal(2,1) + (randomnumber*Normal(2,1)); %Generate the
                                                        %initial Lc Matrix
    lc = LC(2,1);
    chktol = 0;
        theta = thetavalue(lc,chktol);      %Call function 'thetavalue'
        RFC(1,1) = theta;

    monthtype = getmonth(startmonth);
    daytype = getday(startweekday);

    ln = Normal(2,1); lm = MCL(2,1); ls = SCL(2,1);

    DufVal = getDufVal(1,ln,lm,ls,lc);
    DUFalpha(1,monthtype,daytype,1) = DufVal;


%-----------------------------------------------------------------------
%Defining the initial values for the variables required
%-----------------------------------------------------------------------

    chktol = 0;         %A Variable used to check the status of tolerance crossing
    chktolasone = 1;    %A Variable used to check the time, ck stays as 1
    chksevere = 0;      %Variable that checks the time to change to Severe
                          %Constained Load
    hour = 1;           %A variable used as a counter
    FTSA = TSA - 1;

%-----------------------------------------------------------------------
%Generate the realtime load curve (LC) using randomnumber as a %age error
%-----------------------------------------------------------------------

realtimeLn = 1;
realtimeLm = 0;
realtimeLs = 0;

for f = 1:FTSA

    ftsa = f+1;
    hour = hour+1;

        rfc = RFC(1,f); postol = PosTol(1,f); negtol = NegTol(1,f);
            ln = Normal(2,hour);
            lm = MCL(2,hour);
            ls = SCL(2,hour);

    %-------------------------------------------------------------------
    %Assign the Constraint Level
    %-------------------------------------------------------------------


        if rfc >= postol  %Check if the Positve Tolerance limit has been reached
```

```
        chktol = 1;   %This variable stays as 1 till the graph cross NegTol
            chktolasone = chktolasone + 1; %Variable that counts how
                                             %long chktol stays as one.
    end

    if rfc < postol
        if rfc > negtol
            chktolasone = 0;
        end
    end

    if rfc < negtol  %Check if the Negative Tolerance limit has been reached
        chktol = 0;  %This variable stays as 0 till the graph cross PosTol
            chksevere = 0; %Variable that checks the time to change to
                           %Severe Constained Load
    end

    if chktol == 1
        if chktolasone > 2 | chksevere > 6    %Check the condition for
                                             %severe constrained load
            level = 3;
            realtimeLs = realtimeLs + 1;
        else
            level = 2;
            realtimeLm = realtimeLm + 1;
        end
        chksevere = chksevere + 1;
    end

    if chktol == 0
        level = 1;
        realtimeLn = realtimeLn + 1;
    end

%-----------------------------------------------------------------
%-----------------------------------------------------------------

LCVAL = getnewlcval(ln,lm,ls,level);    %Call function 'getnewlcval'
    LC(2,hour) = LCVAL;

theta = thetavalue(LCVAL,chktol);       %Call function 'thetavalue'

if ftsa <= TSA
    RFC(1,ftsa) = RFC(1,f) +  theta;        %Storing the RFC matrix
end


%-----------------------------------------------------------------
%Checking for the type of Month and Type of Day
%-----------------------------------------------------------------

monthtype = getmonth(startmonth);
daytype = getday(startweekday);

%%----------------------------------------------------------------
%%Assigning the DUF values for the variables DUFalpha, DUFbeta and DUFgama
%%----------------------------------------------------------------
```

```
            if LCVAL > ln
                DUFalpha(level,monthtype,daytype,hour) =
(DUFalpha(level,monthtype,daytype,hour)+[(LCVAL-lm)/(ln-lm)])/2;
                DUFbeta(level,monthtype,daytype,hour) = 1;
                DUFgama(level,monthtype,daytype,hour) = 1;
            end

            if (LCVAL < ln) & (LCVAL >lm)
                DUFalpha(level,monthtype,daytype,hour) =
(DUFalpha(level,monthtype,daytype,hour)+[(LCVAL-lm)/(ln-lm)])/2;
                DUFbeta(level,monthtype,daytype,hour) = 1;
                DUFgama(level,monthtype,daytype,hour) = 1;
            end


            if LCVAL == ln
                DUFalpha(level,monthtype,daytype,hour) = 1;
                DUFbeta(level,monthtype,daytype,hour) = 1;
                DUFgama(level,monthtype,daytype,hour) = 1;
            end

            if LCVAL == lm
                DUFalpha(level,monthtype,daytype,hour) = 0;
                DUFbeta(level,monthtype,daytype,hour) = 1;
                DUFgama(level,monthtype,daytype,hour) = 1;
            end

            if (LCVAL < lm) & (LCVAL > ls)
                DUFalpha(level,monthtype,daytype,hour) = 0;
                DUFbeta(level,monthtype,daytype,hour) =
(DUFbeta(level,monthtype,daytype,hour)+[(LCVAL-ls)/(lm-ls)])/2;
                DUFgama(level,monthtype,daytype,hour) = 1;
            end

            if LCVAL == ls
                DUFalpha(level,monthtype,daytype,hour) = 0;
                DUFbeta(level,monthtype,daytype,hour) = 0;
                DUFgama(level,monthtype,daytype,hour) = 1;
            end

            if LCVAL < ls
                DUFalpha(level,monthtype,daytype,hour) = 0;
                DUFbeta(level,monthtype,daytype,hour) = 0;
                DUFgama(level,monthtype,daytype,hour) =
(DUFgama(level,monthtype,daytype,hour)+[LCVAL/(ls)])/2;
            end

    %%----------------------------------------------------------------
    %%----------------------------------------------------------------

if ftsa <= TSA
    NL(1,ftsa)=Normal(2,hour);
    ML(1,ftsa)=MCL(2,hour);
    SL(1,ftsa)=SCL(2,hour);
    ControlLoad(1,ftsa)=LC(2,hour);
end

    if hour == 24
        hour = 0;
```

```
        startdate = addtodate(startdate, 1, 'day');
        startmonth = datestr(startdate, 5);
        startweekday = datestr(startdate, 8);

    end

end

%---------------------------------------------------------------------
%Assign the initial values for the Load Curves
%---------------------------------------------------------------------

    NL(1,1) = Normal(2,1);
    ML(1,1)= MCL(2,1);
    SL(1,1) = SCL(2,1);
    ControlLoad(1,1) = LC(2,1);
    ForecastLoad(1,1) = FLC(2,1);

%---------------------------------------------------------------------
%-------------------- Show statistics -------------------------------
%---------------------------------------------------------------------

forecastLn
realtimeLn
forecastLm
realtimeLm
forecastLs
realtimeLs

str1 = ['Normal      ',num2str(forecastLn/24),'
',num2str(realtimeLn/24)];
str2 = ['Medium      ',num2str(forecastLm/24),'
',num2str(realtimeLm/24)];
str3 = ['Severe      ',num2str(forecastLs/24),'
',num2str(realtimeLs/24)];

disp('          Forecast    Realtime')
disp(str1)
disp(str2)
disp(str3)

%---------------------------------------------------------------------
%----------------------- Save the DUFmatrices -----------------------
%---------------------------------------------------------------------
------

    save DUFalpha.mat;
    save DUFbeta.mat;
    save DUFgama.mat;


%---------------------------------------------------------------------
%Plot the Fuel consumption curves
%---------------------------------------------------------------------

    figure;                              %Open a new Figure window
    xaxis = 1:1:TSA;
```

```
    plot(xaxis,PH(2,:),'*-b');                %Plot PHI curve
    set(gca, 'XTick', 1:24:TSA);
    set(gca, 'XTickLabel', [ 0:1:TSAD ] );

        xlabel('Time (days)');               %Label the x-axis as Time
        ylabel('Rate of Fuel Consumption (liters/hour)'); %Label the y-
                                                          %axis as Load
        hold on;
    plot(xaxis,PosTol(1,:),'.-r');            %Plot Max Tolerence curve
    plot(xaxis,NegTol(1,:),'.-g');            %Plot Min Tolerence curve
    plot(xaxis,RFC(1,:),'.--k');              %Plot RFC curve
    plot(xaxis,FRFC(1,:),'.--m');              %Plot RFC curve


    legend('PHI','MaxTol','MinTol','RFC','Forcast RFC',2); %Insert
                                                            %Legend
    title('Fuel Consumption Curves');            %Insert Figure Title


%--------------------------------------------------------------------
%Plot the three Load Curves and the Controlled Load Curve in Figure 1
%--------------------------------------------------------------------

    figure;                                   %Open a new Figure window
    xaxis = 1:1:TSA;

    plot(xaxis,NL(1,:),'x-m');             %Plot the Normal Load curve
    set(gca, 'XTick', 1:24:TSA);
    set(gca, 'XTickLabel', [ 0:1:TSAD ] );
        xlabel('Time (days)');                %Label the x-axis as Time
        ylabel('Load (kW)');                  %Label the y-axis as Load
        hold on;         %Hold the same Figure while the other graphs are drawn
    plot(xaxis,ML(1,:),'o-b');             %Plot the Medium Constrained Curve
    plot(xaxis,SL(1,:),'+-r');            %Plot the Severely Constrained Curve
    plot(xaxis,ControlLoad(1,:),'.:k');    %Plot the Controlled Load Curve in
                                             %Figure 1.
    plot(xaxis,ForecastLoad(1,:),'*:g');  %Plot the Forecast Load Curve in
                                             %Figure 1.

    legend('Normal','MCL','SCL','Realtime Load','Load
Forecast','Location','BestOutside','Orientation','horizontal');
%Insert Legend
    title('Load Curves');                %Insert the Figure Title


function theta = thetavalue(lc,level)

load Gen40.mat;
load Gen60.mat;
load Gen80.mat;

if level == 1
    if lc <= (160*.25)
        theta = Gen60(2,1);
    elseif lc <= 80
        theta = Gen60(2,2);
    elseif lc <= (160*.75)
        theta = Gen60(2,3);
```

```
    else
        theta = Gen60(2,4);
    end
elseif level == 2
    if lc <= (128*.25)
        theta = Gen40(2,1);
    elseif lc <= (128*.5)
        theta = Gen40(2,2);
    elseif lc <= (128*.75)
        theta = Gen40(2,3);
    else
        theta = Gen40(2,4);
    end
elseif level == 3
    if lc <= (80*.25)
        theta = Gen80(2,1);
    elseif lc <= (80*.5)
        theta = Gen80(2,2);
    elseif lc <= (80*.75)
        theta = Gen80(2,3);
    else
        theta = Gen80(2,4);
    end

end

function daytype = getday(startweekday)

    switch startweekday
        case{'Mon','Tue','Wed','Thu','Fri'}
            daytype = 1;
        otherwise
            daytype = 2;
end

function monthtype = getmonth(startmonth)

    switch startmonth
        case{'12','01','02'}
            monthtype = 1;
        case{'03','04','05'}
            monthtype = 2;
        case{'06','07','08'}
            monthtype = 3;
        case{'09','10','11'}
            monthtype = 4;
end

function DufVal = getDufVal(level,ln,lm,ls,LCVAL);

        if level == 1
            DufVal = (LCVAL/ln) - 1;
        end

        if level == 2
            DufVal = (LCVAL/lm) - 1;
        end

        if level == 3
```

```
        DufVal = (LCVAL/ls) - 1;
    end

function LCVAL = getlcval(ln,lm,ls,level);

    if level == 1
        low = -0.1; high = 0.1;
        randomnumber = low + (high-low)*rand;

        LCVAL = ln + (randomnumber*ln);
    end

    if level == 2
        low = -0.2; high = 0.2;
        randomnumber = low + (high-low)*rand;

        LCVAL = lm + (randomnumber*lm);
    end

    if level == 3
        low = -0.3; high = 0.3;
        randomnumber = low + (high-low)*rand;

        LCVAL = ls + (randomnumber*ls);
    end

function PHImax = getphival(R,Thr)

    PHImax = R / Thr;
```

A9. Ethical approval obtained from the Maldives government to conduct the survey

Department of National Planning

Ministry of Finance and Treasury

Finance Building, Ameenee Magu, Male' 20379, Rep. of Maldives

No: 100-ST3/PRIV/2012/109

10th July 2012

Mr. Miraz Mohamed Fulhu
PhD Research Student
University of Canterbury
New Zealand

Dear Mr. Miraz Mohamed Fulhu

<u>Active Human Intelligence for Smart Grid (HISG): Feedback Control pf Remote Power Systems</u>

With reference to your application form, we hereby approve conducting of the above mentioned survey from 01st August to 15th October 2012.

Attached please find the official form "Permission to Conduct Survey" .We would appreciate it if you could inform us if there is any change in the survey period.

Yours sincerely,

Aishath Shahuda
Deputy Executive Director

Email:info@planning.gov.mv Website:www.planing.gov.mv Fax: (960) 3327351 Operator: (960) 3348383

Department of National Planning,
Ministry of Finance and Treasury
Finance Building, Ameenee Magu, Male' 20379
Male', Republic of Maldives

PERMISSION TO CONDUCT SURVEY

1. Name of Organisation/ Individual : Miraz Mohamed Fulhu
2. Survey title : Active Human Intelligence for Smart Grid (HISG): Feedback Control of Remote Power Systems
3. Survey objectives : To understand the energy (mainly electrical) usage pattern of typical island communities of the Maldives, their willingness and ability to adjust power consumption, especially in an energy constrain situation.
4. Period of data collection : 01 August 2012 to 15 October 2012
5. Survey areas (Atoll/Island) : A Dh. Fenfushi
6. Government authorities consulted:
   1) Department of National Planning
   2)
   3)

Under the Statistical Regulation of the Republic of Maldives, we hereby give permission to undertake the above mentioned survey.

Name: Aishath Shahuda

Signature:

Designation: Deputy Executive Director

Date: 10/07/2012

DEPARTMENT OF NATIONAL PLANNING
Seal
Republic of Maldives

FOR THE ATTENTION OF RESPONDENTS

Under the Statistical Regulation of Republic of Maldives :-

Any person, who is authorised by the Department of National Planning, Ministry of Finance and Treasury to conduct a survey, shall be provided with true information, within the permitted time.

The work of any person permitted to carry out a survey under this regulation shall not be hindered or obstructed

Confidentiality will be accorded to any information that is obtained from permitted data collection operations, which would disclose the identity of the provider.

A10. Human Ethics Committee approval obtained from the University of Canterbury

UNIVERSITY OF CANTERBURY
Te Whare Wānanga o Waitaha
CHRISTCHURCH NEW ZEALAND

HUMAN ETHICS COMMITTEE

Secretary, Lynda Griffioen
Email: human-ethics@canterbury.ac.nz

Ref: HEC 2012/86

30 July 2012

Miraz Mohamed Fulhu
Department of Mechanical Engineering
UNIVERSITY OF CANTERBURY

Dear Miraz

The Human Ethics Committee advises that your research proposal "Active human intelligence for smart grid (HISG) feedback control of remote power systems" has been considered and approved.

Please note that this approval is subject to the incorporation of the amendments you have provided in your email of 25 July 2012.

Best wishes for your project.

Yours sincerely

Michael Grimshaw
Chair
University of Canterbury Human Ethics Committee

University of Canterbury Private Bag 4800, Christchurch 8140, New Zealand. www.canterbury.ac.nz

E S